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FINAL REPORT
OIL CONTAMINATION IN OXYGEN SYSTEMS

Contract NObs-94416
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FOREWORD

This report covers the work performed under NAVSHIPS Contract No. NObs-94416 (Project No. SF013-08-14, Task 3917). The NAVSEC contract monitor was Mr. Herman Kraut.

The objective of this program was to collect the necessary experimental data on ignition and flame propagation in an oil contaminated oxygen system in order to more exactly define the required level of cleanliness for such systems. The results are to be incorporated into military specifications for oxygen systems to define the required cleanliness.

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| | |
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INTRODUCTION

Under auspices of the Department of the Navy, NAVSEC, a study was undertaken to determine the compression ignition and flame propagation limits of hydrocarbons in a high pressure oxygen system.

Considerable work has been done concerning compression ignition and flame propagation in high pressure air systems, but very little has been done with pressurized oxygen systems. The limited work performed with oxygen did not employ conditions corresponding to the specific systems now in use, namely 3000 psi oxygen with 1/2" monel piping. The program reported herein was designed to study that specific area.

The study was primarily concerned with the determination of the acceptable levels of oil contamination (2190) on the internal surface of a 1/2" monel pipe below which compression ignition and flame propagation will not occur when pressurized with 3000 psi oxygen. It was also desired to determine that level of oil contamination where, upon ignition, a pressure rise will not exceed 25%.

The first phase of the program consisted of a literature survey to assemble and review all available information from previous studies in the area of compression ignition and flame propagation in high pressure air and oxygen systems. A summary of these earlier studies is presented in Section I.

Following the literature survey a test program was designed and initiated to accomplish the objectives of the contract. A description of the test apparatus used is presented in Section II, the testing procedure is described in Section III, and the results of the test program are presented in Section IV.

Throughout this report, the term "oil concentration" is used. This refers to the amount of oil coating, expressed as mg/ft^2 , on the inside surface of the test pipe.

SUMMARY

A test program was conducted to determine the ignition limits of oil contamination in 1/2" monel pipe when pressurized with 3000 psi oxygen. The oils investigated were 2190 lubricating oil and Habcoc #318 cutting oil. Thin films of these oils were applied to the internal surface of a 4 ft. section of 1/2" monel pipe. The pipe was then rapidly pressurized with 3000 psi oxygen. In addition, tests were made using oil droplets and varying the initial pipe wall temperature.

The test results showed little danger of compression ignitions at oil concentrations below 160 mg./ft² of 2190, or below 110 mg./ft² for Habcoc. Concentrations of both oils above 260 mg./ft² will ignite when rapidly pressurized with 3000 psi oxygen. These concentrations must be compared to the present oxygen clean standards of 0.013 mg./ft² maximum allowable hydrocarbon concentration.

The results also showed that ignition will not occur with oil droplets or puddles smaller than 100 μ in size and that a pressure rise greater than 25% will not occur below oil concentrations of 500 mg./ft².

As a result of this test program, it is recommended that the oxygen clean standards be relaxed to 1.5 mg./ft². The level of oil concentration is a factor of 100 below the lower ignition limits defined by this test program. It is felt that such a safety factor more than compensates for any variation in the lower ignition limit due to effective pipe length, wall temperature, and non-uniformity in oil contamination.

I LITERATURE SURVEY

In recent years the phenomenon of compression ignition in pneumatic systems has been extensively studied. Such ignitions are induced in systems contaminated with sufficient quantities of a combustible organic material and exposed to rapid pressurization with an oxidizing gas.

Most of the work was concerned with high pressure air systems contaminated with lubricating oil from air compressors. Faeth and White⁽¹⁾ conducted a series of tests in which they investigated the combustion characteristics of 25 mg. samples of various lubricating oils placed at the dead end of a pipe exposed to rapid pressurization with air. They defined the combustion ranges as functions of various parameters including the rate of pressurization, air pressure, length of pipe, and the initial ambient system temperature. The results of these tests quantify the expected trends due to variation in the parameters. Of interest was the fact that the occurrence of combustion was greater, the shorter the length of pipe used down to a length of 1 ft. However, the change in combustion limit was only a mild function of the pipe length.

Wilson⁽²⁾ and co-workers investigated the compression ignition characteristics of lubricating oils evenly coated on the internal surface of a 1 1/2" diameter test pipe. Using a 15 ft. length of pipe, they studied both auto-ignition and flame propagation using 2190 and Callulube lubricating oils. Wilson defined the lower combustible limit in the range of 1000 mg./ft² of oil. He also found that used degraded oil was much more reactive than new unused oils - attributing this to breakdown products in the oil. This conclusion was later verified by Zabetakis⁽³⁾. Both Wilson⁽²⁾ and Perlee⁽⁴⁾, concerned with this type of ignition caused by degraded oil blow-by from air compressors, recommend proper cleaning and maintenance to prevent dangerous conditions from arising.

Faeth⁽¹⁾ did a theoretical analysis of the rapid compression process in an attempt to predict whether conditions for ignition would exist in a given system. Predictions based on his analysis compared well with his observed experimental data.

Dallinger and McGill⁽⁶⁾, concerned with high pressure air systems aboard submarines, surveyed work done in this field. They reported that an increase in pipe diameter increased the temperatures obtained during a rapid compression, thus lowering the concentration of oil necessary for ignition.

Russian interest in the problem of compression ignition with oxygen is indicated by the work of Gordeyev and coworkers⁽⁷⁾. They reported lower explosive limits of 26,000 mg./ft² of oil and lower combustion limits of 190 mg./ft². However, they used oils with Russian designations, making comparison with 2190 difficult, and they failed to report pertinent parameters such as rates of pressurization and pipe diameters.

The dangers inherent in high pressure air systems, due to compression ignition, lead to questions about parallel phenomenon in high pressure oxygen systems. Baum⁽⁸⁾ and his coworkers investigated 7500 psi oxygen systems, looking at effects of system temperature, vibration, shock, extended storage, contamination, and material compatibility. In regard to ignition, Baum⁽⁸⁾ recommended "absolute" cleanliness from organics, and homogeneous hydrocarbon concentrations less than 50 ppm.

In 1961, Kehat⁽⁹⁾ studied ignition and flame propagation at pressures up to 1500 psi using gaseous oxygen. Using a 1/4" test pipe evenly coated with oil, he used a spark and an electric match to induce ignition. Kehat found no significant danger of ignition at concentrations up to 1000 mg./ft² of oil. Also of interest was Kehat's technique of evenly coating a small diameter pipe, 1/2", with oil - namely of dissolving the oil in a solvent, carbon tetrachloride, applying the solution to the pipe, and then allowing the solvent to evaporate, leaving a thin film of oil behind.

A summary of the literature survey is presented in Section 4.2.2 and compared with the recommendations of this current test program.

II TEST APPARATUS

2.1 General Description

The basic test apparatus is illustrated schematically in Figure 1.

The test apparatus basically consisted of a four foot section of 1/2 inch, schedule 80, monel pipe plugged at one end. The high pressure oxygen was supplied from a two tank system. One tank (15 ft³ capacity) at 3800 psig was used to supply the second tank (9 ft³) at 3000 psig which, in turn, supplied the test pipe. The instrumentation and control equipment consisted of flame probes, pressure transducers, thermocouples, external strain gauges, a 5000 psi relief valve, a gas sampling bomb, a manually operated ball valve, a quick opening Marotte valve, a check valve and a manually operated vent valve. Photographs of the test pipe, in place for a run, are shown in Figures 2, 3, 4, and 5. A more detailed description of the components is found in Table I.

A four foot length of pipe was selected as the optimum length. This selection is a compromise between the minimum length recommended by Faeth and White and the physical instrumentation requirements necessary to measure flame propagation.

This test apparatus was modified slightly during the test program to accommodate a sparking device. This alteration consisted of removing the pressure transducer (P_1) closest to the dead end and replacing it with the sparking device. This modification is shown in Figure 6.

In addition to the pipe just described, another test pipe was used during the final portion of testing with a minimum of instrumentation located adjacent to the dead end. This second pipe was also a 4 ft. length of 1/2" monel pipe, but it had only two instrumentation taps and a vent line. This test set up is shown schematically in Figure 7. Photographs of this test set up are shown in Figures 8 and 9. As can be seen in the figures a nichrome heating coil was added to the pipe to give the capability of operating at elevated initial temperatures.

TABLE I
LIST OF APPARATUS AND COMPONENTS

| <u>Component</u> | <u>Description</u> |
|---|--|
| 1 3000 psig O ₂ supply flask | 9 ft ³ , MIL-C-1511A |
| 1 3800 psig O ₂ supply flask | 15 ft ³ , MIL-C-28C9B |
| 1 Solenoid valve | Marotta M.V. 173 |
| 1 Pressure gauge | 0 to 10,000 psig scale |
| 1 Check valve | 3/4" |
| 3 Nipples | 3/4" pipe, NiCu |
| 1 Pipe union | 1/2", NiCu |
| 1 Pipe cap | 1/2", NiCu |
| 1 Flame arrestor* | 1/2" I.P.S. NiCu |
| 1 Pipe tee | 3/4" monel |
| 1 Test pipe | 4 ft. Sch. 80, 1/2" Monel MIL-T-1368 Ty. 1, Cond. 1 |
| 1 Relief valve | 5,000 psi relieve pressure |
| 1 Ball valve | 3/4", manual |
| 1 Vent valve | 1/4", manual |
| 1 Gas sampler bomb | See Section 2.2 |
| 4 Strain gauges | " |
| 3 Pressure transducers | " |
| 3 Temperature probes | " |
| 4 Flame probes | " |

*The flame arrestor used in Runs A-1 through A-24, Runs D-1 through D-5, and F-36 was made of stainless steel.

For safety considerations, the test pipe was located in a concrete test pit and was surrounded by sand bags. The control and instrumentation read-outs were located in an adjacent test pit.

2.2 Instrumentation

Instrumentation on the basic test set-up consisted of four flame probes spaced 12 inches apart; three pressure transducers, 18 inches apart; four external strain gauges; and three thermocouples, 18 inches apart. The locations of this instrumentation can be seen in the figures presented in the previous section.

In addition to this basic instrumentation, a sparking device was used in an attempt to induce ignitions. The location of this sparking device can also be seen in the figures presented in the previous section. The outputs of the instrumentation probes were recorded on an oscillograph recorder with a paper speed of 64 inches/sec.

A close-up of a flame probe, a thermocouple, and the sparking device is shown in Figure 10; while a photograph of a pressure transducer, a strain gauge installation and the flame arrestor is shown in Figure 11.

A block diagram of the basic instrumentation is presented in Figure 12, while a schematic of the control circuitry is shown in Figure 13. A detailed list and description of the major instrumentation components is presented in Table II. The time sequence in which all the instrumentation and control circuitry operated is shown in Figure 14.

The instrumentation block diagram (Figure 12) shows the relationship of the control circuitry and the instrumentation probes to the recording device. The flame probes, the pressure transducers, and the strain gauges are energized by the circuitry; signals detected by them are then transmitted to the recorder. The thermocouples, using an ice water bath as a reference, generate voltages indicative of their temperatures and transmit them to the recorder. The sparking

TABLE II
LIST OF INSTRUMENTATION EQUIPMENT

| <u>Description</u> | <u>Manufacturer</u> |
|---|--|
| 1. Chromel/alumel thermocouples (400 milliseconds response time) | Thermoelectric, Inc. |
| 2. Chromel wire flame probes - porcelain base with 300 volt operating potential (< 1.7 millisecond response time) | Electric Boat Division (not commercial) |
| 3. Pressure transducers - 10,000 lbs/in ² , air cooled type (.05 millisecond response time) | Norwood, Model 102 |
| 4. UV light beam oscillograph recorder - galvanometer (1.7 millisecond response time) | Consolidated Electrodynamics Corp. (C.E.C.), Model #124 |
| 5. 3 kc. carrier amplifiers for recorder (15 units) | C.E.C., Model #1-113B |
| 6. Modulators for amplifiers (7 units) (2 milliseconds response time) | C.E.C., Model #15-605 |
| 7. Oscillator power supplies (2 units) | C.E.C., Model #2-105B |
| 8. Variable AC Voltage Supply | Superior Electric |
| 9. Displacement Transducer (< 1.7 millisecond response time) | Underwater Explosion Research Division (USN) |
| 10. Potentiometer and Switch (Auxilliary temperature measurements) | Leeds & Northrup |
| 11. 120 OHM Strain Gauges | Baldwin-Lima-Hamilton |

device discharges the electrical energy stored in its capacitors (Figure 13B) and this event is transmitted to the recorder. The potentiometer attached to the stem of the Marotta valve is energized by the circuitry and transmits the change in position of the valve to the recorder. The Marotta valve itself is activated by the control circuitry; while time delay relay 1 (TD-1) and (TD-2) are activated by the same circuitry and in turn control parts of this circuitry (Figure 13).

As seen in Figure 13A, the circuitry is activated by closing switch S-1 which energizes the indicating light plus the flasher and bell to warn personnel in the area that a test is in progress. A test is initiated by closing S₃ which activates relay K₁ and TD-1. Activation of relay K₁ closes contacts K₁₋₁ which keeps itself activated without regard to the position of S₃. Activation of TD-1 closes the contacts TD1-1 which, in turn, activates TD-2, TD-3, and opens the Marotta valve. Activation of TD-2, after a preset period of time, shuts down the circuitry. Activation of TD-3, after a preset period of time, opens contacts TD3-1, closing the Marotta valve.

The circuitry of Figure 13B is activated by the closing of TD3-2, which has been closed by TD-3 of Figure 13A. With the contact TD3-2 closed, TD-5 is activated which in turn closes contacts TD5-1 activating K₂. K₂ closes contact K₂₋₁ which discharges the spark. The 600 μ F capacitors are charged by closing switch S₄. Contacts TD3-3 isolate this circuit while TD-3 is activated.

III TEST PROCEDURE

3.1 Preliminary Tests

Before proceeding with ignition tests, it was necessary to verify the proposed oil coating technique.

Preliminary tests were conducted to determine whether the oil coating technique selected would be satisfactory. This technique consisted of dissolving the oil in a low-boiling, non-combustible solvent Freon TF and then applying the resultant solution to the pipe. Upon evaporation of the Freon, a residual coating of oil was left on the pipe. In evaluating this technique, a sacrificial section of pipe was used. After the coating operation, the pipe was cut into small sections and the amount of oil present on each section was determined by chemical analysis. This analysis consisted of removing the oil from the pipe segments with a low boiling point solvent, then evaporating off the solvent. The amount of oil removed from each segment was then determined gravimetrically.

This same method of evaluation was used to determine the feasibility of other oil coating techniques as part of the verification. The other oil coating techniques evaluated were: a) applying the oil directly with a circular brush or swab, b) spraying the oil onto the pipe, c) partial removal of a heavy oil coating using a solvent.

3.2 Test Plan

The test plan included the following areas of investigation:

- 1) The coating of the test pipe with various concentrations of 2190 oil at ambient temperatures and attempting a compression ignition with 3000 psi oxygen; the oil coatings were increased in small increments in concentrations ranging from 0.08 mg/ft² to 640 mg/ft².
- 2) Placing droplets of 2190 oil near the dead end of the test pipe

and attempting a compression ignition with 3000 psi oxygen; the size of the oil droplets used ranged from 5 microliters ($\mu\ell$) to 90 $\mu\ell$. 3) Employing the combination of coating the test pipe with 2190 oil and placing a droplet of the oil near the dead end of the pipe, and attempting a compression ignition with 3000 psi oxygen; oil coating concentrations ranged from 12 mg/ft^2 to 88 mg/ft^2 , while the oil droplets ranged in size from 10 $\mu\ell$ to 100 $\mu\ell$. 4) Coating the test pipe with various concentrations of 2190 oil or of Habcool cutting oil, using an electrical spark to induce ignition in a 3000 psi oxygen atmosphere; the 2190 oil concentrations ranged from 0.16 mg/ft^2 to 640 mg/ft^2 , while the Habcool concentrations ranged from 100 mg/ft^2 to 480 mg/ft^2 . 5) Coating a modified test pipe (minimum instrumentation) with various concentrations of 2190 oil and of Habcool cutting oil, and attempting a compression ignition with 3000 psi oxygen; the 2190 oil concentrations ranged from 30 mg/ft^2 to 480 mg/ft^2 , while the Habcool concentration ranged from 160 mg/ft^2 to 480 mg/ft^2 .

The 2190 (MIL-L-17331A) lubricating oil was selected to be used during this test program because most of the previous investigations of compression ignition and flame propagation were performed using this lubricating oil. Thus, in order to compare results with the earlier work, 2190 was used in this investigation. Habcool #318 cutting oil was selected as a typical organic cutting oil used in a machine shop with which piping might be contaminated during fabrication in actual practice.

3.3 Testing Procedure

In making a test run the following procedure was used:

1. The test pipe was thoroughly cleaned by use of Freon (TF) rinses and a lint-free cloth.
2. With the instrumentation probes replaced by plugs, the pipe was filled with an oil/Freon solution of a known concentration.
3. The oil/Freon solution was emptied and the remaining Freon allowed to evaporate (15 to 20 minutes was allowed) leaving a thin, uniform oil film.
4. The instrumentation probes were replaced into their proper positions.
5. The test pipe was placed "on-line", putting the flame arrester into position within the union.
6. The calibration of the instrumentation was checked as well as the electrical control circuitry.
7. The position of all hand-operated valves was checked.
8. The test area was cleared of all personnel and the test was made.
9. After the run was completed, the electrical power was turned off and all valves secured.
10. A gas sample was taken for analysis and the test pipe was vented down to ambient pressure.
11. The test pipe was disconnected and was visually inspected.
12. The test pipe and instrumentation probes were thoroughly cleaned in preparation for the next run.

The gas sample at the conclusion of a test was analyzed for carbon dioxide, hydrogen, carbon monoxide, oxygen and nitrogen using gas chromatography.

No attempt was made to replace the air in the test pipe with pure O_2 before the rapid pressurization. This initial air is compressed to within $1/4$ " of the dead end during compression from 14.7 psi to 3000 psi and it was felt that this small amount of nitrogen, in comparison to the amount of oxygen present, would have a negligible effect on the results.

IV TEST RESULTS

4.1 Preliminary Tests

The oil coating tests showed that the selected technique of dissolving the oil in a non-combustible solvent, Freon 12, gave the best results. The oil was evenly coated onto the surface of the pipe and the concentration of oil on the pipe was proportional to the concentration of oil in the Freon. This relationship is shown in Table III. It was also found to be the best technique from an operational point of view - being less prone to technician error and having good reproducibility.

TABLE III
OIL COATING CONCENTRATIONS
(1/2" Monel Pipe)

| <u>Oil Concentration in Freon - PPM</u> | <u>Oil Coating on Pipe - mg/ft²</u> | <u>Oil Film Thickness - microns</u> |
|---|--|---|
| 5 | 0.0125 | 1.2×10^{-3} |
| 10 | 0.025 | 2.4×10^{-3} |
| 100 | 0.25 | 2.4×10^{-2} |
| 1000 | 2.5 | 0.24 |
| 10,000 | 24.6 | 2.4 |
| 50,000 | 123.0 | 12.0 |
| 100,000 | 246.0 | 24.0 |
| 200,000 | 492.0 | 48.0 |
| 300,000 | 738.0 | 72.0 |

4.2 Ignition Test Results

The results of the test program are presented in the following sections. The significant data are presented in Section 4.2.1 and Appendix A, while an interpretation and discussion of these data is found in Section 4.2.2.

4.2.1 Data

The parameters measured during each of the test runs are presented in Appendix A. The parameters include: oil concentration, ambient temperature, maximum pressure, rate of pressure rise, incident temperature, flame probe saturation, and strain gauge indication. The temperatures presented are the maximum temperatures recorded. Due to the lag and response time of the thermocouples, the actual temperatures experienced are much higher.

It should be noted that at various points throughout the test program blank runs were made - i.e. runs in which no oil was put into the test pipe. These runs were made to determine the time histories of the various parameters due only to the rapid pressurization of the test pipe with oxygen, and to serve as a check on the instrumentation. The results of all the blank runs were identical, therefore, the results of only one of these runs is presented.

4.2.2 Correlation and Interpretation of Results

The first test run with oil contamination resulted in a violent explosion causing extensive damage to the test apparatus. This damage is shown in Figures 15-20. A comparison can be made with the undamaged test pipe shown in previous sections.

As can be seen in the figures a two inch section of the test pipe, at the inlet end, was disintegrated along with part of the couplings; one of the pressure probes was blown out of its fitting; several of the electrical connectors to the instrumentation probes were burned; and the copper "O" ring seals on the two remaining pressure transducers were blown out. In addition, the flame arrestor was disintegrated and the check valve welded closed. It should be noted that for this run the coupling at the inlet end of the test pipe and the flame arrestor were both made of stainless steel.

After the explosion, it was felt that the level of oil contamination, 160 mg/ft^2 , was well into the explosive range and that the testing should be conducted in a much lower range of oil concentration. Subsequent test runs showed, however, that levels of oil contamination higher than 160 mg/ft^2 can withstand rapid pressurization by pure oxygen without resulting in an explosion. These subsequent tests employed monel and nickel-copper components only, while the initial run at 160 mg/ft^2 , which resulted in an explosion, had a stainless

steel flame arrestor. In an attempt to duplicate the explosive run, a stainless steel flame arrestor was put into the system (Run F-3). In this run, though the test pipe did not rupture, there was an ignition and flame propagation, as opposed to no indications of ignition or flame propagation under the same conditions using a monel flame arrestor (Run F-18).

No completely satisfactory explanation of the explosion is available, but it is significant that no indications of ignition were obtained with the monel flame arrestor, while very definite indications were observed with the stainless steel flame arrestor.

As a result of the explosion in the first run, subsequent tests were conducted (Runs A2-A24, F1-F28, F35) by evenly coating the test pipe with 2190 oil with concentrations of 0.08 mg./ft² up to 160 mg./ft² without any indication of ignition. At oil concentrations between 173 mg./ft² and 266 mg./ft² there were indications of ignition and flame propagation on some instrumentation probes but not on others. At oil concentrations above 266 mg./ft², there were definite indications of ignition and flame propagation. These results can be seen graphically in Figure 21.

On the supposition that it was possible to have sufficient oil in the test pipe to propagate a flame while not having a high enough concentration to cause an auto-ignition, a series of runs were conducted in which it was attempted to induce an ignition. Thus runs (Runs D1-D14, AD1-AD10) were made with small drops of oil placed near the dead end of the test pipe (thus giving a high local concentration of oil). Oil droplets ranging in size from 5 μ l to 100 μ l were used alone and in combination with a uniform oil film ranging in concentrations from 12 mg./ft² to 88 mg./ft². In Run D-12, the gas analysis after the run revealed the presence of CO₂, indicating combustion of the oil. However, the other instrumentation did not confirm this combustion, and the results could not be duplicated in subsequent tests at similar or more severe conditions (Runs AD-8 and AD-10).

In the test runs with oil droplets of 70 μ l or greater, H_2 was found in the gas after the test run. It is believed that this H_2 is a product of the thermal decomposition of the oil. However, oil droplets were used only in an attempt to induce ignitions. This they failed to do, so the appearance of H_2 , though interesting, was not investigated further. However, two things should be noted in this regard: 1) the occurrence of oil droplets, 70 μ l or greater, in a clean oxygen system is highly unlikely and 2) the H_2 appeared in concentrations well below its lower ignition limit.

Having failed to induce ignition using small droplets of oil, an attempt was made to induce ignition by means of an electrical spark. A series of runs were made using the sparking device (Runs F1-F28, F35, F36). In those runs in which ignitions were observed, they were of the compression ignition type, and involved oil concentrations above 160 mg./ft². The spark did not initiate any ignitions nor affect flame propagation in any way.

Test runs made in which the pipe was evenly coated with Habcool at 70°F (Runs F29-F34) indicated that the no ignition range was below about 110 mg./ft², while the ignition range was somewhere above 250 mg./ft². Comparison of these results with those obtained for 2190 (Figure 21) show Habcool to be somewhat more reactive.

In an attempt to attain higher temperatures from the rapid compression with pure oxygen, a series of tests were run using a pipe with a minimum of instrumentation located adjacent to the dead end. Because of the minimum amount of instrumentation, it was more difficult to get accurate indications of ignition and flame propagation. However, from the instrumentation available, the following results were obtained:

- A. Using 2190 oil at 70°F, tests were run at concentrations of 80 mg./ft² to 480 mg./ft² (Runs C1-C6). No ignition was obtained.

below 160 mg/ft^2 , while the ignition range was found to be above 200 mg/ft^2 . These results approximate the results shown in Figure 21.

- B. Using 2190 oil heated to 125°F , tests were run at concentrations ranging from 160 mg/ft^2 to 480 mg/ft^2 (Runs C7-C11). Indications of ignition were seen at the lower concentration of 160 mg/ft^2 , indicating that the level of oil contamination necessary for ignition and flame propagation are somewhat lower at 125°F than at 70°F .
- C. Using Habcool cutting oil at 70°F , tests were run at concentrations ranging from 160 mg/ft^2 to 480 mg/ft^2 (Runs C12-C16). Definite ignitions were obtained above 200 mg/ft^2 , while the non-ignition range is somewhere below 160 mg/ft^2 . The non-ignition and ignition ranges are about the same as those found with the regular test pipe.
- D. Using Habcool oil at 125°F , tests were run at concentrations ranging from 160 mg/ft^2 to 480 mg/ft^2 (Runs C17-C21). The results from these tests were not distinguishable from those at 70°F .

A more quantitative correlation can be made by plotting the resultant % CO_2 , the maximum recorded temperature, and maximum pressure obtained as functions of level of oil concentration. Such plots are shown in Figures 22, 23 and 24. It can be seen that these results match the non-ignition, transient, and ignition ranges earlier defined more qualitatively.

The carbon dioxide found was considerably less than would be dictated with 100% combustion of the oil. This is, however, consistent with the fact that carbon deposits and residual oil were found in the test pipe after ignitions, indicating considerably less than complete combustion.

It is possible to compare these results with those obtained by earlier investigators. Kehat reports little danger of ignition in oxygen

systems up to 1500 psig at concentrations up to 1000 mg/ft². This compares to our lower ignition limit of 160 mg/ft² at 3000 psi. Kehat used a pure compound, n-hexadecane, for his work, while our work was performed with a commercial lubricating oil, 2190. Comparison of the properties of n-hexadecane and 2190 - e.g., molecular weights, auto-ignition temperature - and considering the differences in the oxygen pressures used reveal our results to be in reasonable agreement with Kehat.

It is also possible to compare our results with the results of Wilson et al. Wilson reports the lower ignition limit in high pressure air systems at 3000 psig of 2190 oil to be 1000 mg/ft². By extrapolating these results to pure oxygen at 3000 psig, a lower ignition limit would be approximately 200 mg./ft². This is in good agreement with the current results.

A summary comparison of the current results and those obtained by earlier investigators is presented in the following chart:

| <u>Investigator</u> | <u>Test Gas</u> | <u>Test Apparatus</u> | <u>Oil Used</u> | <u>Lower Ignition Limit</u> |
|---------------------|---------------------------|--|---------------------------------|-----------------------------|
| Kehat | O ₂ , 1500 psi | 1/2" pipe | C ₁₂ H ₂₆ | 1000 mg/ft ² |
| Wilson | Air, 3000 psi | 1-1/2" pipe | 2190 | 1000 mg/ft ² |
| Gordeyev | O ₂ | - | - | 190 mg/ft ² |
| Presti | O ₂ , 3000 psi | 1/2" pipe | 2190 | 160 mg/ft ² |
| Baum | O ₂ , 1500 psi | (50 ppm homogeneous mixture - recommended lower limit) | | |

V CONCLUSIONS AND RECOMMENDATIONS

From the test results obtained the following conclusions can be drawn for 3000 psi oxygen systems:

1. Compression ignition and flame propagation will not occur below oil concentrations of 160 mg/ft^2 at oil temperatures below 125°F in a $1/2"$, schedule 80, monel pipe.
2. Compression ignitions will not occur with oil droplets or puddles smaller than 100μ in size.
3. Habcool cutting oil was found to be somewhat more reactive than 2190.
4. Present oxygen clean standards (as specified by Shipyard Standard Practice 1.9 Rev. F, Oxygen and Nitrogen Systems, paragraph 3.2.3.1d) which require oil film concentrations of 0.013 mg/ft^2 or less, are much too rigorous and can be relaxed. The oil film concentration of 0.013 mg/ft^2 corresponds to obtaining a concentration of 5 ppm in a Freon rinse, while 160 mg/ft^2 corresponds to 65,000 ppm in Freon.

It is recommended that the allowable oil film concentration specified by the above Shipyard Standard Practice be set at 500 ppm oil concentration in a freon rinse. This concentration allows a safety factor of 100 over the values at which oil ignitions begin to occur.

It is felt that such a safety factor more than adequately allows for any variation in the lower ignition limit due to variations in effective pipe lengths below 4 feet which might be found in an actual pressurized oxygen system.

5. To obtain pressure rises greater than 25% requires oil concentrations greater than 500 ng./ft². This can be seen from Figure 24.

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APPENDICES

ASTM D 153
Oxygen Permeation Test

| DATE | RUN NO. | CONC. (mg/ft ²) | AMBI- ENT TEMP. (°F) | MAXIMUM PRESSURE IN X TIME (psig in x msec) | | | RATE OF PRESSURE RISE INSIDE PIPE (psig/sec) | MAXIMUM INSIDE P. (°F in x msec) | |
|-------|---------|--------------------------------|-------------------------------|--|----------------|----------------|---|-------------------------------------|----------------|
| | | | | P ₁ | P ₂ | P ₃ | | P ₁ | P ₂ |
| | BLANK | 0 | 70 | 3000 in 100 | 3000 in 100 | 3000 in 100 | 26000 | 200 in 100 | 100 in 100 |
| 10/6 | A-1 | 160 | 70 | >3000 in 90 | >3000 in 90 | >3000 in 90 | 20900 | >2000 in 100 | >2000 in 100 |
| 10/21 | A-2 | 0.08 | 70 | 3000 in 100 | 3000 in 100 | 3000 in 100 | 23000 | 200 in 100 | 100 in 100 |
| 10/24 | A-3 | 0.16 | 70 | | | | | SAME AS RUN A-2 | |
| 10/24 | A-4 | 0.32 | 70 | | | | | SAME AS RUN A-2 | |
| 10/25 | A-5 | 0.64 | 70 | | | | | SAME AS RUN A-2 | |
| 10/26 | A-6 | 1.60 | 70 | | | | | SAME AS RUN A-2 | |
| 10/26 | A-7 | 2.13 | 70 | | | | | SAME AS RUN A-2 | |
| 10/26 | A-8 | 2.67 | 70 | | | | | SAME AS RUN A-2 | |
| 10/27 | A-9 | 3.20 | 70 | | | | | SAME AS RUN A-2 | |
| 10/27 | A-10 | 4.00 | 70 | | | | | SAME AS RUN A-2 | |
| 10/27 | A-11 | 5.25 | 70 | | | | | SAME AS RUN A-2 | |
| 10/28 | A-12 | 7.82 | 70 | | | | | SAME AS RUN A-2 | |
| 10/28 | A-13 | 10.3 | 70 | | | | | SAME AS RUN A-2 | |
| 10/28 | A-14 | 12.8 | 70 | | | | | SAME AS RUN A-2 | |
| 10/31 | A-15 | 20.0 | 70 | | | | | SAME AS RUN A-2 | |
| 10/31 | A-16 | 24.6 | 70 | | | | | SAME AS RUN A-2 | |
| 11/1 | A-17 | 35.6 | 70 | | | | | SAME AS RUN A-2 | |
| 11/2 | A-18 | 45.7 | 70 | | | | | SAME AS RUN A-2 | |
| 11/2 | A-19 | 55.2 | 70 | | | | | SAME AS RUN A-2 | |
| 11/2 | A-20 | 64.0 | 70 | | | | | SAME AS RUN A-2 | |
| 11/14 | A-21 | 72.3 | 70 | 2900 in 139 | 2700 in 139 | 2700 in 139 | 28000 | 225 in 100 | 150 in 100 |
| 11/15 | A-22 | 80.0 | 70 | 2960 in 141 | 2800 in 141 | 2800 in 141 | 28000 | 240 in 100 | 170 in 100 |

A

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1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024, 2025, 2026, 2027, 2028, 2029, 2030, 2031, 2032, 2033, 2034, 2035, 2036, 2037, 2038, 2039, 2040, 2041, 2042, 2043, 2044, 2045, 2046, 2047, 2048, 2049, 2050, 2051, 2052, 2053, 2054, 2055, 2056, 2057, 2058, 2059, 2060, 2061, 2062, 2063, 2064, 2065, 2066, 2067, 2068, 2069, 2070, 2071, 2072, 2073, 2074, 2075, 2076, 2077, 2078, 2079, 2080, 2081, 2082, 2083, 2084, 2085, 2086, 2087, 2088, 2089, 2090, 2091, 2092, 2093, 2094, 2095, 2096, 2097, 2098, 2099, 2100, 2101, 2102, 2103, 2104, 2105, 2106, 2107, 2108, 2109, 2110, 2111, 2112, 2113, 2114, 2115, 2116, 2117, 2118, 2119, 2120, 2121, 2122, 2123, 2124, 2125, 2126, 2127, 2128, 2129, 2130, 2131, 2132, 2133, 2134, 2135, 2136, 2137, 2138, 2139, 2140, 2141, 2142, 2143, 2144, 2145, 2146, 2147, 2148, 2149, 2150, 2151, 2152, 2153, 2154, 2155, 2156, 2157, 2158, 2159, 2160, 2161, 2162, 2163, 2164, 2165, 2166, 2167, 2168, 2169, 2170, 2171, 2172, 2173, 2174, 2175, 2176, 2177, 2178, 2179, 2180, 2181, 2182, 2183, 2184, 2185, 2186, 2187, 2188, 2189, 2190, 2191, 2192, 2193, 2194, 2195, 2196, 2197, 2198, 2199, 2200, 2201, 2202, 2203, 2204, 2205, 2206, 2207, 2208, 2209, 2210, 2211, 2212, 2213, 2214, 2215, 2216, 2217, 2218, 2219, 2220, 2221, 2222, 2223, 2224, 2225, 2226, 2227, 2228, 2229, 2230, 2231, 2232, 2233, 2234, 2235, 2236, 2237, 2238, 2239, 2240, 2241, 2242, 2243, 2244, 2245, 2246, 2247, 2248, 2249, 2250, 2251, 2252, 2253, 2254, 2255, 2256, 2257, 2258, 2259, 2260, 2261, 2262, 2263, 2264, 2265, 2266, 2267, 2268, 2269, 2270, 2271, 2272, 2273, 2274, 2275, 2276, 2277, 2278, 2279, 2280, 2281, 2282, 2283, 2284, 2285, 2286, 2287, 2288, 2289, 2290, 2291, 2292, 2293, 2294, 2295, 2296, 2297, 2298, 2299, 2300, 2301, 2302, 2303, 2304, 2305, 2306, 2307, 2308, 2309, 2310, 2311, 2312, 2313, 2314, 2315, 2316, 2317, 2318, 2319, 2320, 2321, 2322, 2323, 2324, 2325, 2326, 2327, 2328, 2329, 2330, 2331, 2332, 2333, 2334, 2335, 2336, 2337, 2338, 2339, 2340, 2341, 2342, 2343, 2344, 2345, 2346, 2347, 2348, 2349, 2350, 2351, 2352, 2353, 2354, 2355, 2356, 2357, 2358, 2359, 2360, 2361, 2362, 2363, 2364, 2365, 2366, 2367, 2368, 2369, 2370, 2371, 2372, 2373, 2374, 2375, 2376, 2377, 2378, 2379, 2380, 2381, 2382, 2383, 2384, 2385, 2386, 2387, 2388, 2389, 2390, 2391, 2392, 2393, 2394, 2395, 2396, 2397, 2398, 2399, 2400, 2401, 2402, 2403, 2404, 2405, 2406, 2407, 2408, 2409, 2410, 2411, 2412, 2413, 2414, 2415, 2416, 2417, 2418, 2419, 2420, 2421, 2422, 2423, 2424, 2425, 2426, 2427, 2428, 2429, 2430, 2431, 2432, 2433, 2434, 2435, 2436, 2437, 2438, 2439, 2440, 2441, 2442, 2443, 2444, 2445, 2446, 2447, 2448, 2449, 2450, 2451, 2452, 2453, 2454, 2455, 2456, 2457, 2458, 2459, 2460, 2461, 2462, 2463, 2464, 2465, 2466, 2467, 2468, 2469, 2470, 2471, 2472, 2473, 2474, 2475, 2476, 2477, 2478, 2479, 2480, 2481, 2482, 2483, 2484, 2485, 2486, 2487, 2488, 2489, 2490, 2491, 2492, 2493, 2494, 2495, 2496, 2497, 2498, 2499, 2500, 2501, 2502, 2503, 2504, 2505, 2506, 2507, 2508, 2509, 2510, 2511, 2512, 2513, 2514, 2515, 2516, 2517, 2518, 2519, 2520, 2521, 2522, 2523, 2524, 2525, 2526, 2527, 2528, 2529, 2530, 2531, 2532, 2533, 2534, 2535, 2536, 2537, 2538, 2539, 2540, 2541, 2542, 2543, 2544, 2545, 2546, 2547, 2548, 2549, 2550, 2551, 2552, 2553, 2554, 2555, 2556, 2557, 2558, 2559, 2560, 2561, 2562, 2563, 2564, 2565, 2566, 2567, 2568, 2569, 2570, 2571, 2572, 2573, 2574, 2575, 2576, 2577, 2578, 2579, 2580, 2581, 2582, 2583, 2584, 2585, 2586, 2587, 2588, 2589, 2590, 2591, 2592, 2593, 2594, 2595, 2596, 2597, 2598, 2599, 2600, 2601, 2602, 2603, 2604, 2605, 2606, 2607, 2608, 2609, 2610, 2611, 2612, 2613, 2614, 2615, 2616, 2617, 2618, 2619, 2620, 2621, 2622, 2623, 2624, 2625, 2626, 2627, 2628, 2629, 2630, 2631, 2632, 2633, 2634, 2635, 2636, 2637, 2638, 2639, 2640, 2641, 2642, 2643, 2644, 2645, 2646, 2647, 2648, 2649, 2650, 2651, 2652, 2653, 2654, 2655, 2656, 2657, 2658, 2659, 2660, 2661, 2662, 2663, 2664, 2665, 2666, 2667, 2668, 2669, 2670, 2671, 2672, 2673, 2674, 2675, 26

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| DATE | RUN NO. | CONC. (mg/ft ²) | AMBI- ENT TEMP. (°F) | MAXIMUM PRESSURE IN X TIME (psig in x msec) | | | RATE OF PRESSURE RISE INSIDE PIPE (psig/sec) | MAXIMUM DISCHARGE (cm ³ in x sec) | |
|-------|---------|--------------------------------|-------------------------------|--|----------------|----------------|---|---|----------------|
| | | | | P ₁ | P ₂ | P ₃ | | T ₁ | T ₂ |
| | | 2190 | | | | | | | |
| 11/15 | A23 | 87.2 | 70 | 3000 in 143 | 2800 in 143 | 2760 in 143 | 27000 | 240 in 153 | 165 in 105 |
| 11/15 | A-24 | 94.1 (μl) | 70 | 2940 in 141 | 2800 in 141 | 2740 in 141 | 23000 | 225 in 160 | 160 in 100 |
| 11/3 | D-1 | 5 | 70 | 3000 in 133 | 2800 in 133 | 2760 in 133 | 28500 | 250 in 165 | 175 in 100 |
| 11/4 | D-2 | 10 | 70 | | | | | SAME AS RUN A-2 | |
| 11/4 | D-3 | 15 | 70 | | | | | SAME AS RUN A-2 | |
| 11/7 | D-4 | 20 | 70 | | | | | SAME AS RUN A-2 | |
| 11/7 | D-5 | 5 | 70 | | | | | SAME AS RUN A-2 | |
| 11/18 | D-6 | 30 | 70 | 2900 in 105 | 2800 in 105 | 2720 in 105 | 37000 | 210 in 135 | 160 in 100 |
| 11/18 | D-7 | 40 | 70 | 2900 in 104 | 2800 in 109 | 2760 in 109 | 35000 | 225 in 180 | 160 in 100 |
| 11/21 | D-8 | 50 | 70 | 2950 in 101 | 2840 in 101 | 2760 in 101 | 33500 | 235 in 195 | 150 in 100 |
| 11/21 | D-9 | 60 | 70 | 2950 in 104 | 2880 in 104 | 2760 in 104 | 36500 | 215 in 175 | 150 in 100 |
| 11/22 | D-10 | 70 | 70 | 2920 in 105 | 2840 in 105 | 2720 in 105 | 36500 | 215 in 155 | 150 in 100 |
| 11/22 | D-11 | 80 | 70 | 2940 in 105 | 2720 in 105 | 2720 in 105 | 38000 | 225 in 190 | 160 in 100 |
| 11/23 | D-12 | 90 | 70 | 3100 in 97 | 2760 in 97 | 2650 in 97 | 42000 | 245 in 285 | 200 in 165 |
| 11/8 | D-13 | 10 | 125 | | | | | SAME AS RUN A-2 | |
| 11/9 | D-14 | 10 (Habeool) | 125 | | | | | SAME AS RUN A-2 | |
| 11/9 | AD-1 | 12.3+ 10 μl | 125 | | | | | SAME AS RUN A-2 | |
| 11/10 | AD-2 | 24.6+ 10 μl | 125 | | | | | SAME AS RUN A-2 | |
| 11/10 | AD-3 | 35.6+ 10 μl | 125 | | | | | SAME AS RUN A-2 | |

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1. ...
2. ... 55,000 rpm/min

| S | T ₁ | T ₂ | MAXIMUM CUTABLE TEMP. (°F) | GAS TEMPERATURE INDICATION IN X TESTS (°F/in in X msec) | | | | FLAME PROBE INDICATION TIME (msec) | | | | PER- CENT CO ₂ |
|----|----------------|----------------|-------------------------------------|--|----------------|----------------|----------------|--|----------------|----------------|----------------|---------------------------------|
| | | | | S ₁ | S ₂ | S ₃ | S ₄ | F ₁ | F ₂ | F ₃ | F ₄ | |
| 1 | 103 | 100 in 20 | 70 | 150 in 103 | 150 in 103 | 150 in 103 | 150 in 103 | - | - | - | - | 0 |
| 2 | 10 | 100 in 21 | 70 | 150 in 101 | 150 in 101 | 150 in 101 | 150 in 101 | - | - | - | - | 0 |
| 3 | 10 | 100 in 20 | 70 | 150 in 103 | 150 in 103 | 150 in 103 | 150 in 103 | - | - | - | - | 0 |
| 4 | 10 | 100 in 20 | 70 | 150 in 105 | 150 in 105 | 150 in 105 | 150 in 105 | - | - | - | - | 0 |
| 5 | 10 | 100 in 10 | 70 | 150 in 109 | 150 in 109 | 150 in 109 | 150 in 109 | - | - | - | - | 0 |
| 6 | 10 | 100 in 20 | 70 | 150 in 101 | 150 in 101 | 150 in 101 | 150 in 101 | - | - | - | - | 0 |
| 7 | 10 | 110 in 10 | 70 | 150 in 104 | 150 in 104 | 150 in 104 | 150 in 104 | - | - | - | - | 0 |
| 8 | 10 | 100 in 20 | 70 | 150 in 105 | 150 in 105 | 150 in 105 | 150 in 105 | - | - | - | - | 0 |
| 9 | 95 | 95 in 10 | 70 | 150 in 105 | 150 in 105 | 150 in 105 | 150 in 105 | - | - | - | - | 0 |
| 10 | 106 | 100 in 106 | 70 | 150 in 97 | 150 in 97 | 150 in 97 | 150 in 97 | - | - | - | - | 6.58 |
| | | | | | | | | | | | | 1.1% H ₂ |
| | | | 125 | | | | | | | | | |
| | | | 125 | | | | | | | | | |
| | | | 125 | | | | | | | | | |
| | | | 125 | | | | | | | | | |
| | | | 125 | | | | | | | | | |

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SECTION 1 - TESTS

Oxygen Concentration in Air

| DATE | RUN NO. | CONC. (mg/ft ²) | AMBI- ENT TEMP. (°F) | MAXIMUM PRESSURE IN X TUBE (psig in x msec) | | | RATE OF PRESSURE RISE INSIDE PIPE (psig/sec) | MAXIMUM TEMPERATURE | |
|-------|---------|--------------------------------|-------------------------------|--|----------------|----------------|---|---------------------|-----------------|
| | | | | P ₁ | P ₂ | P ₃ | | T ₁ | T ₂ |
| | | 2190 | | | | | | | |
| 11/10 | AD-1 | 45.7+ 10 µl | 125 | | | | | | SAME AS RUN A-2 |
| 11/14 | AD-5 | 64.0+ 10 µl | 125 | | | | | | SAME AS RUN A-2 |
| 11/28 | AD-6 | 55.2+ 70 µl | 70 | | | | 12000 | | SAME AS RUN A-2 |
| 11/29 | AD-7 | 64.0+ 80 µl | 70 | | | | 16000 | | SAME AS RUN A-2 |
| 11/29 | AD-8 | 72.2+ 90 µl | 70 | | | | 18000 | | SAME AS RUN A-2 |
| 11/30 | AD-9 | 80.0+ 100 µl | 70 | 2920 in 109 | 2840 in 109 | 2720 in 109 | 17000 | 280 in 300 | 105 in 100 |
| 11/30 | AD-10 | 87.2+ 100 µl | 70 | 2880 in 106 | 2760 in 106 | 2720 in 106 | 16000 | 230 in 350 | 115 in 100 |
| 3/30 | F-1 | 0.16 | 70 | | | | 38000 | | SAME AS RUN A-2 |
| 3/30 | F-2 | 1.60 | 70 | | | | 38000 | | SAME AS RUN A-2 |
| 3/31 | F-3 | 7.81 | 70 | | | | 38000 | | SAME AS RUN A-2 |
| 3/31 | F-4 | 15.2 | 70 | | | | 38000 | | SAME AS RUN A-2 |
| 3/31 | F-5 | 24.6 | 70 | | | | 38000 | | SAME AS RUN A-2 |
| 4/3 | F-6 | 35.6 | 70 | | | | 38000 | | SAME AS RUN A-2 |
| 4/3 | F-7 | 45.8 | 70 | | | | 38000 | | SAME AS RUN A-2 |
| 4/3 | F-8 | 55.2 | 70 | | | | 38000 | | SAME AS RUN A-2 |
| 4/4 | F-9 | 64.0 | 70 | | | | 32000 | | SAME AS RUN A-2 |
| 4/4 | F-10 | 72.3 | 70 | | | | 38000 | | SAME AS RUN A-2 |
| 4/4 | F-11 | 80.0 | 70 | | | | 38000 | | SAME AS RUN A-2 |
| 4/4 | F-12 | 87.2 | 70 | | | | 38000 | | SAME AS RUN A-2 |

A

INJECTION RATE: 100

Flow rate: 100,000 gal/sec

| INJECTION RATE | | MATERIAL OUTSIDE TEMP. (°F) | DEPART GASES & INJECTION IN X SECS (min/hr. in X msec) | | | | FLAME PROBE EXTINGUISHING TIME (msec) | | | | PER- CENT CO ₂ |
|----------------|-----------|--------------------------------------|---|----------------|----------------|----------------|---|----------------|----------------|----------------|---------------------------------|
| S | T | | S ₁ | S ₂ | S ₃ | S ₄ | P ₁ | P ₂ | P ₃ | P ₄ | |
| | | 125 | | | | | | | | | 0 |
| | | 125 | | | | | | | | | 0 |
| | | 70 | | | | | | | | | 0 |
| | | 70 | | | | | | | | | 1.4% H ₂ |
| | | 70 | | | | | | | | | 1.3% H ₂ |
| | | 70 | | | | | | | | | 1.0% H ₂ |
| 5-1-102 | 105 in 25 | 70 | 150 in 109 | 150 in 109 | 150 in 109 | 150 in 109 | 20 | 20 | 20 | 20 | 0 |
| 5-1-100 | 95 in 20 | 90 | 155 in 106 | 150 in 106 | 150 in 106 | 155 in 106 | - | - | - | - | 0 |

B

| DATE | RUN NO. | CONC. (mg/ft ²) | AMBI- ENT TEMP. (°F) | MAXIMUM PRESSURE IN X TIME (psig in x msec) | | | RATE OF PRESSURE RISE INSIDE PIPE (psig/sec) | MAXIMUM PRESSURE | |
|----------------|---------|-----------------------------|-------------------------------|--|----------------|----------------|---|------------------|----------------|
| | | | | P ₁ | P ₂ | P ₃ | | T ₁ | T ₂ |
| 4/5 | F-13 | 107 | 70 | | | | 38000 | SAME AS RUN A-2 | |
| 6/6 | F-14 | 120 | 70 | | | | 38000 | SAME AS RUN A-2 | |
| 6 | F-15 | 133 | 70 | | | | 38000 | SAME AS RUN A-2 | |
| 4/7 | F-16 | 147 | 70 | 3000 in 100 | 3000 in 100 | 3000 in 100 | 38000 | 200 in 100 | 140 in 100 |
| 7 | F-17 | 147 | 70 | | | | 38000 | SAME AS RUN A-2 | |
| 4/7 | F-18 | 160 | 70 | | | | 38000 | SAME AS RUN A-2 | |
| 7/10 | F-19 | 133+ 104 | 70 | 3000 in 100 | 3000 in 100 | 3000 in 100 | 38000 | 200 in 100 | 140 in 100 |
| 10 | F-20 | 173 | 70 | | 2930 in 121 | 2680 in 121 | 34500 | 207 in 582 | 230 in 582 |
| 12 | F-21 | 173 | 70 | | | 2800 in 100 | 35000 | 203 in 300 | 100 in 300 |
| 7/12 | F-22 | 266 | 70 | | 3000 in 102 | 3000 in 102 | 38000 | 205 in 502 | 210 in 502 |
| 13 | F-23 | 266 | 70 | | 2910 in 103 | 2680 in 108 | 40250 | 306 in 500 | 236 in 500 |
| 4/14 | F-24 | 373 | 70 | | 2880 in 83 | 2660 in 83 | 40250 | 345 in 300 | 623 in 300 |
| 18 | F-25 | 480 | 70 | | 2960 in 90 | 2680 in 98 | 43000 | 290 in 550 | 411 in 550 |
| 19 | F-26 | 640 | 70 | | 4000 in 79 | 3720 in 79 | 44000 | 670 in 332 | 775 in 332 |
| 7/20 | F-27 | 640 | 70 | | 4320 in 87 | 3880 in 89 | 40000 | 1034 in 140 | 723 in 140 |
| 24 | F-28 | 640 | 70 | | 4320 in 91 | 4120 in 92 | 38000 | | 429 in 140 |
| 6/15 | F-35 | 640 | 70 | | 3760 in 88 | 3680 in 217 | 66500 | 1194 in 207 | 832 in 137 |
| 16 | F-36 | 160 | 70 | 2940 in 140 | 2760 in 140 | | 28500 | 245 in 277 | 410 in 280 |
| HAZCOOL | | | | | | | | | |
| 26 | F-29 | 160 | 70 | | 3320 in 190 | 3040 in 190 | 35000 | 363 in 244 | 190 in 244 |
| 27 | F-30 | 160 | 70 | | 2800 in 121 | 2520 in 121 | 32000 | 272 in 390 | 190 in 390 |
| 28 | F-31 | 320 | 70 | | 3000 in 125 | 2800 in 125 | 34500 | 420 in 400 | 201 in 400 |
| 28 | F-32 | 320 | 70 | | 3120 in 113 | 2960 in 202 | 35400 | 447 in 510 | 1 in 510 |
| 28 | F-33 | 480 | 70 | | 4680 in 36 | 6520 in 35 | 42000 | 2170 in 103 | 87 in 221 |
| 3 | F-34 | 107 | 70 | | 3000 in 110 | 2950 in 110 | 37000 | 200 in 110 | 110 in 110 |

DATE: 12-10-1964

| NO. | INLET TEMP | T ₃ | THERMOCOUPLE TEMP. (°F) | FLAME PROBE TEMP (°F) (AVERAGE IN 4 PROBES) | | | | FLAME PROBE EXTINGUISHING TIME (msec) | | | | PER- CENT CO ₂ |
|-----|-------------|----------------|-------------------------------|---|------------|------------|------------|---|------|-----|-----|---------------------------------|
| | | | | P 1 | P 2 | P 3 | P 4 | F 1 | F 2 | F 3 | F 4 | |
| 100 | 120 in 100 | 70 | 160 | 160 in 100 | 180 in 100 | 160 in 100 | 160 in 100 | 90 | - | - | - | 0 |
| 110 | 120 in 100 | 70 | 165 | 170 | 180 in 100 | 160 in 100 | 160 in 100 | 100 | 100 | 100 | 100 | <0.10 |
| 120 | 200 in 609 | 70 | 170 | 180 in 100 | 180 in 100 | 180 in 100 | 180 in 100 | - | - | 161 | 161 | 0 |
| 130 | 215 in 20 | 70 | 165 | 160 | 160 in 100 | 160 in 100 | 160 in 100 | - | - | - | - | 0 |
| 140 | 273 in 1202 | 70 | 150 | 160 in 100 | 160 in 100 | 160 in 100 | 160 in 100 | 100 | 100 | 100 | 100 | 0 |
| 150 | 300 in 678 | 70 | 170 | 175 in 100 | 180 in 100 | 180 in 100 | 180 in 100 | 100 | 100 | 100 | 100 | <0.10 |
| 160 | 433 in 600 | 70 | 170 | 186 | 220 in 116 | 180 in 100 | 180 in 100 | 100 | 100 | 100 | 100 | <0.10 |
| 170 | 484 in 1000 | 70 | 150 | 179 | 185 in 100 | 180 in 100 | 180 in 100 | 100 | 100 | 100 | 100 | 0.45 |
| 180 | 650 in 272 | 70 | 190 | 180 | 285 in 246 | 275 in 246 | 280 in 246 | 100 | 100 | 117 | 140 | 2.00 |
| 190 | 745 in 370 | 70 | 290 | 186 | 275 in 73 | 260 in 73 | 260 in 370 | 100 | 85 | 87 | 172 | 2.50 |
| 200 | 934 in 310 | 70 | 295 | 192 | 290 in 250 | 210 in 92 | 200 in 92 | 100 | 93 | 241 | 254 | - |
| 210 | 800 in 280 | 70 | 355 | 219 | 285 in 218 | 235 in 218 | 230 in 217 | 100 | 2 | 147 | 214 | 3.40 |
| 220 | 160 in 420 | 70 | 105 | 140 | 150 in 140 | 140 in 140 | 140 in 140 | 100 | 258 | 351 | 470 | 0.16 |
| 230 | 217 in 144 | 70 | 200 | 112 | 170 in 186 | 180 in 186 | 195 in 186 | 97 | 1000 | 91 | 74 | 0 |
| 240 | 127 in 20 | 70 | 150 | 130 | 140 in 130 | 140 in 130 | 140 in 130 | - | - | - | - | 0 |
| 250 | 261 in 690 | 70 | 180 | 125 | 150 in 125 | 160 in 125 | 160 in 125 | 72 | - | 325 | 500 | 0 |
| 260 | 180 in 850 | 70 | 170 | 100 | 165 in 133 | 160 in 200 | 155 in 123 | 69 | 200 | 320 | 480 | 0.57 |
| 270 | 1270 in 45 | 70 | 465 | 35 | 300 in 35 | 1380 in 35 | 260 in 36 | 34 | 33 | 36 | 36 | 1.95 |
| 280 | 115 in 10 | 70 | 30 | 105 | 150 in 105 | 140 in 105 | 150 in 105 | 2 | - | - | - | 0 |

B

Oxygen Pressure (psig)

| DATE | RUN NO. | CONC. (mg/ft ²) | AMBI-ENT TEMP. (°F) | MAXIMUM PRESSURE IN X TIME (psig in x msec) | | | RATE OF PRESSURE RISE INSIDE PIES (psig/sec) | MAXIMUM PRESSURE (psig) | |
|------|---------|-----------------------------|---------------------|---|----------------|----------------|--|-------------------------|----------------|
| | | | | P ₁ | P ₂ | P ₃ | | T ₁ | T ₂ |
| | | 2190 | | | | | | | |
| 5/8 | C-1 | 80.0 | 70 | 3160 in 108 | - | - | 38600 | | |
| 5/9 | C-2 | 160 | 70 | 3000 in 102 | - | - | 38500 | | |
| 5/9 | C-3 | 240 | 70 | 3160 in 97 | - | - | 42500 | | |
| 5/9 | C-4 | 320 | 70 | 2960 in 104 | - | - | 40000 | | |
| 5/9 | C-5 | 400 | 70 | 3050 in 118 | - | - | 40000 | | |
| 5/9 | C-6 | 480 | 70 | 3240 in 96 | - | - | 45000 | | |
| 5/10 | C-7 | 160 | 125 | 3050 in 100 | - | - | 42500 | 80 | 100 |
| 5/10 | C-8 | 240 | 125 | 3200 in 97 | - | - | 44500 | 80 | 100 |
| 5/10 | C-9 | 320 | 125 | 3070 in 94 | - | - | 40000 | 80 | 100 |
| 5/10 | C-10 | 400 | 125 | 3100 in 90 | - | - | 45000 | 80 | 100 |
| 5/11 | C-11 | 480 | 125 | 3190 in 72 | - | - | 40000 | 80 | 100 |
| | | HABCOOL | | | | | | | |
| 5/11 | C-12 | 160 | 70 | 2910 in 88 | - | - | 45000 | | |
| 5/11 | C-13 | 240 | 70 | 2880 in 87 | - | - | 47500 | | |
| 5/11 | C-14 | 320 | 70 | 2960 in 76 | - | - | 52000 | | |
| 5/12 | C-15 | 400 | 70 | 2910 in 73 | - | - | 43500 | | |
| 5/12 | C-16 | 480 | 70 | 2910 in 70 | - | - | 53500 | | |
| 5/12 | C-17 | 160 | 125 | 2800 in 81 | - | - | 48000 | 80 | 100 |
| 5/12 | C-18 | 240 | 125 | 2890 in 49 | - | - | 51000 | 90 | 110 |
| 5/12 | C-19 | 320 | 125 | 2810 in 80 | - | - | 52000 | 85 | 100 |
| 5/12 | C-20 | 400 | 125 | 3000 in 76 | - | - | 38000 | 90 | 110 |
| 5/12 | C-21 | 480 | 125 | 2900 in 67 | - | - | 50000 | 90 | 110 |

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1000 1000 1000

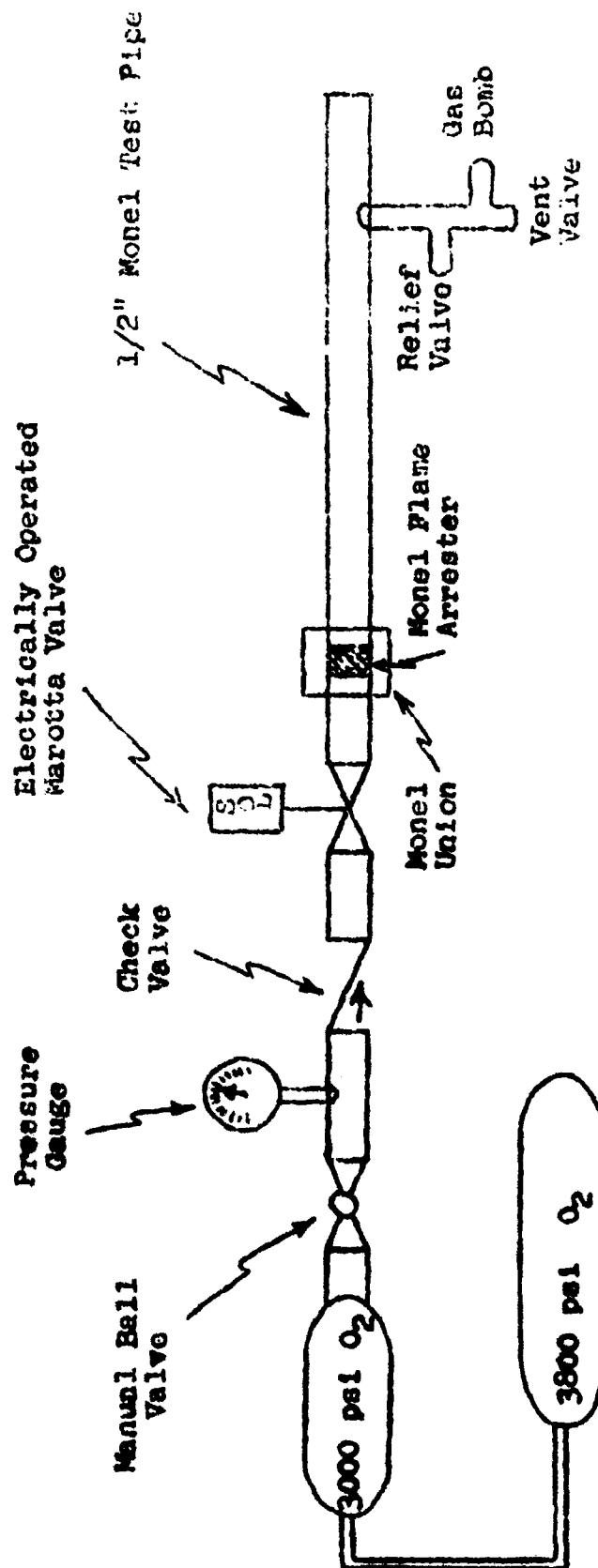
ber 30 1000 1000

| SIDE VENTILATION (cfm) | | | | FLAME PROBE INDICATION TIME (msec) | | | | PER-CENT CO ₂ |
|------------------------|-----|-----|-----|------------------------------------|-----|-----|-----|--------------------------|
| TIME (msec) | | | | TIME (msec) | | | | |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 0 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 0 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 0.62 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 0.32 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 0.68 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 1.97 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 0.23 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 0.23 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 0.45 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 0.77 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 2.25 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 0.12 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 0.50 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 1.32 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 0.46 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 1.85 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 0 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 0.23 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 0.38 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 1.09 |
| 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 1.58 |

B

OIL CONTAMINATION IN OXYGEN SYSTEMS DIAGRAM OF TEST APPARATUS

FIGURE 1



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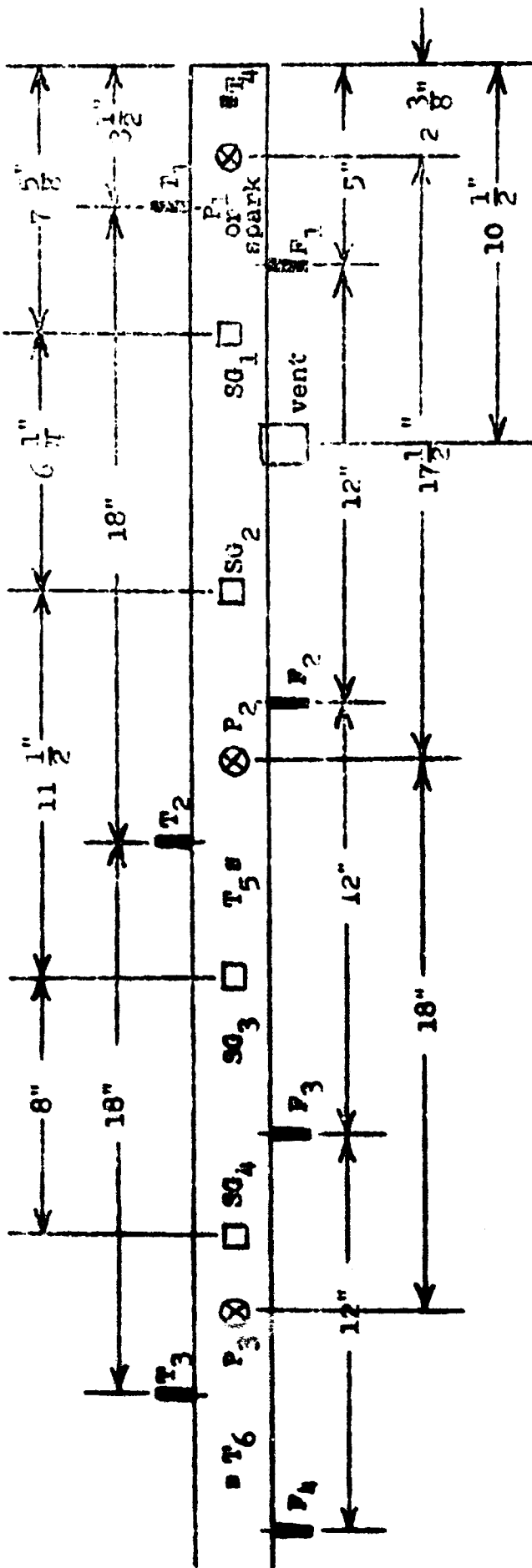
مذہب و ملت کا

I - Thermocouple

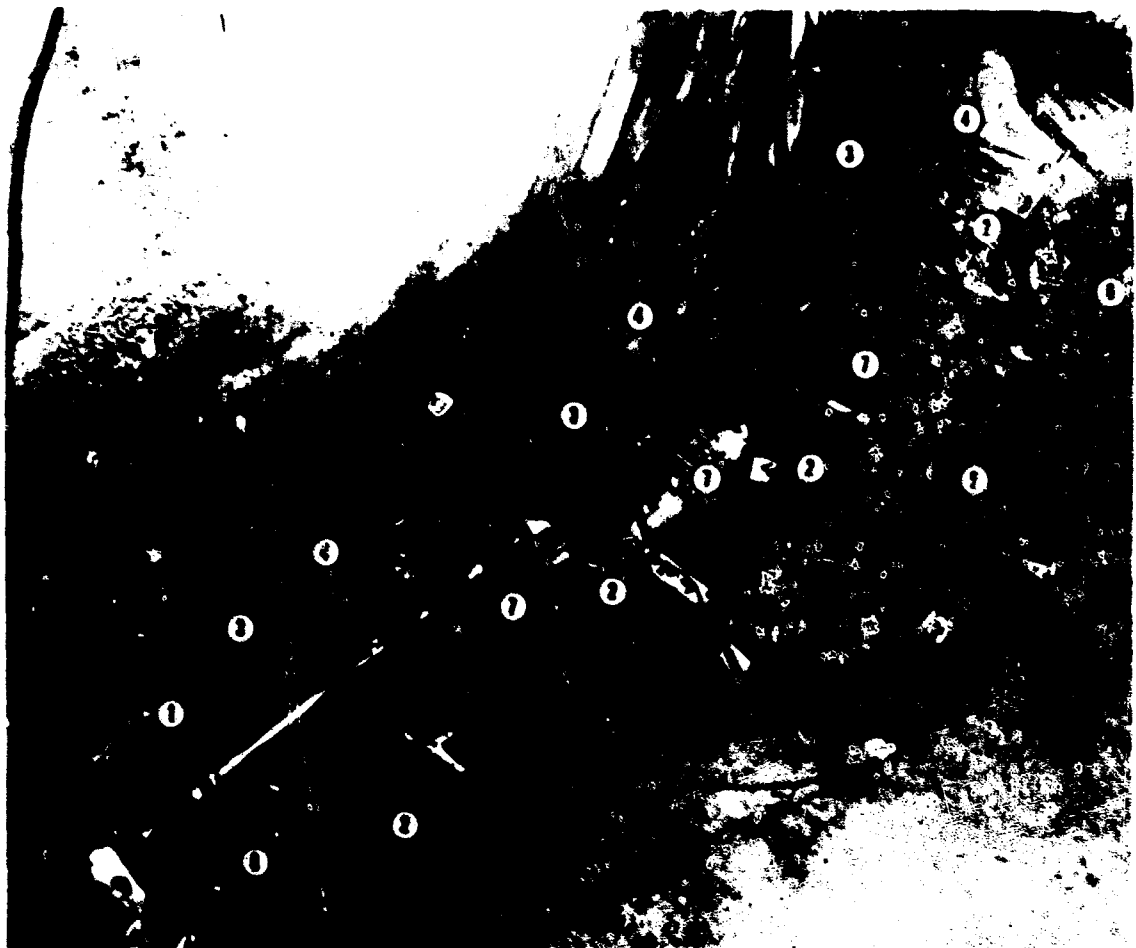
P - Flame Probe

P - Pressure Transducer

SG - Strain Gauge

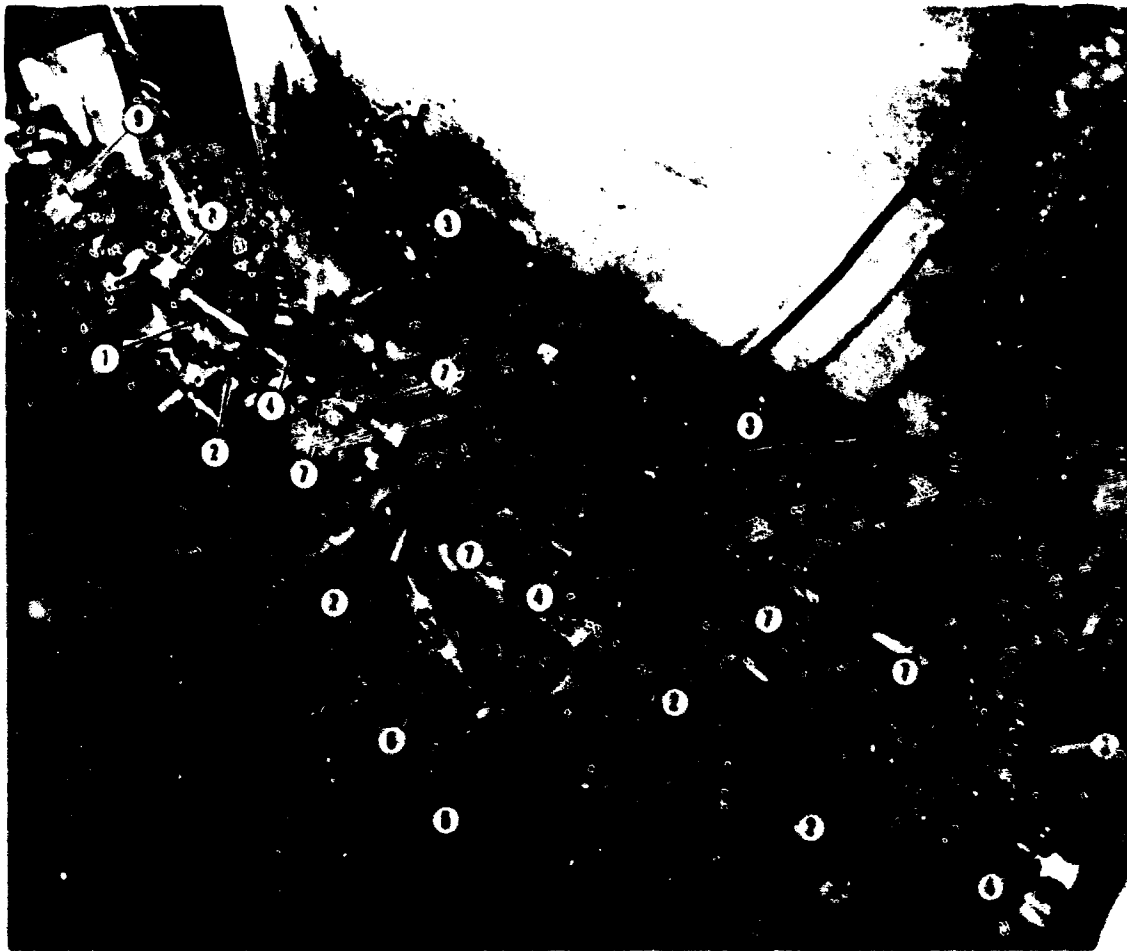


Pipe Length: 48"



TEST PIPE
FIGURE 2

- | | |
|-------------------------|--|
| 1) 1/2" MONEL PIPE | 5) RELIEF VALVE |
| 2) FLAME PROBES | 6) GAS SAMPLE BOMB |
| 3) TEMPERATURE PROBES | 7) STRAIN GAUGES |
| 4) PRESSURE TRANSDUCERS | 8) MONEL UNION (FLAME ARRESTER INSIDE) |



TEST PIPE
FIGURE 3

- | | |
|-------------------------|--------------------|
| 1) 1 1/2" MONEL PIPE | 5) RELIEF VALVE |
| 2) FLAME PROBES | 6) GAS SAMPLE BOMB |
| 3) TEMPERATURE PROBES | 7) STRAIN GAUGES |
| 4) PRESSURE TRANSDUCERS | 8) MC NEIL UNION |
| | 9) MAROTTA VALVE |



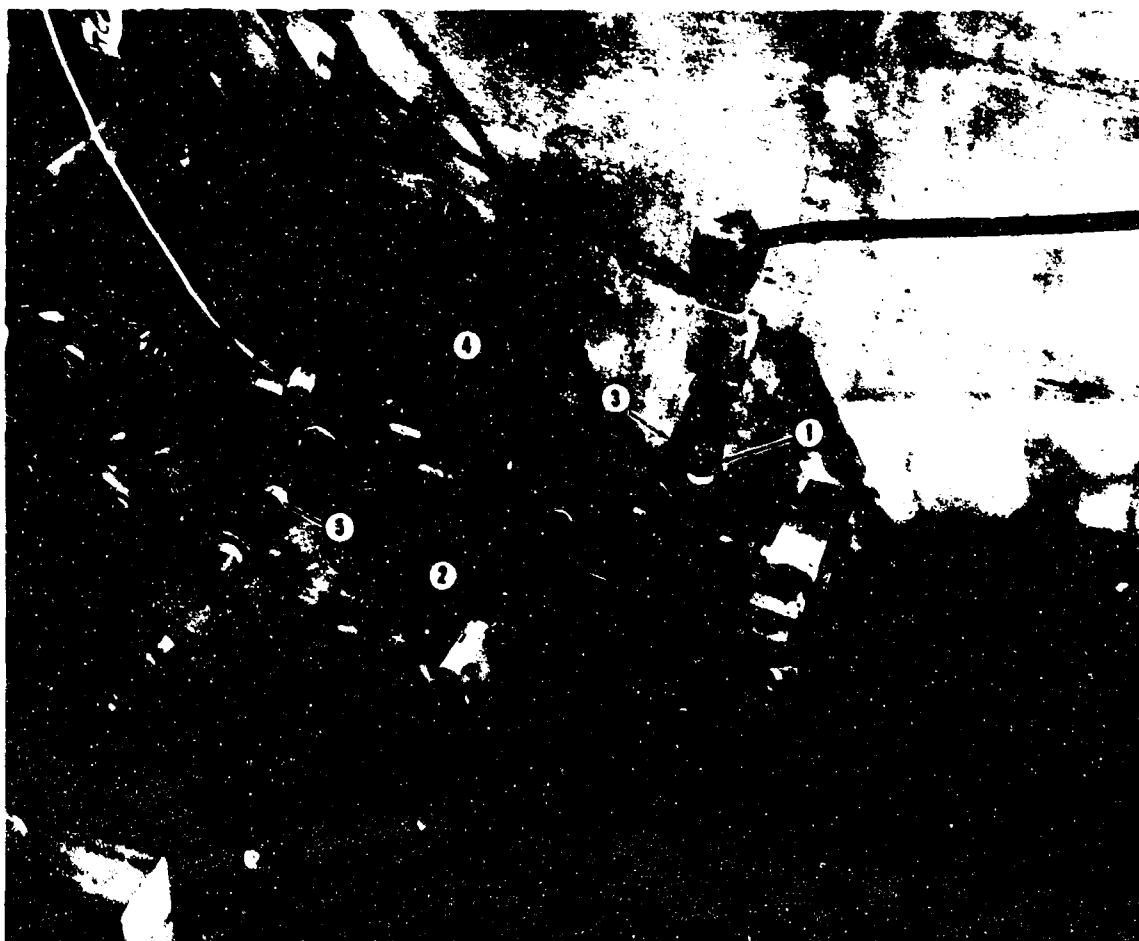
OXYGEN SUPPLY PIPING
FIGURE 4

- 9) MAROTTA VALVE
- 10) CHECK VALVE
- 11) PRESSURE GAUGE
- 12) HAND OPERATED BALL VALVE



OXYGEN SUPPLY PIPING
FIGURE 5

- 10) CHECK VALVE
- 11) PRESSURE GAUGE
- 12) HAND OPERATED BALL VALVE
- 13) 3000 PSI OXYGEN SUPPLY TANK

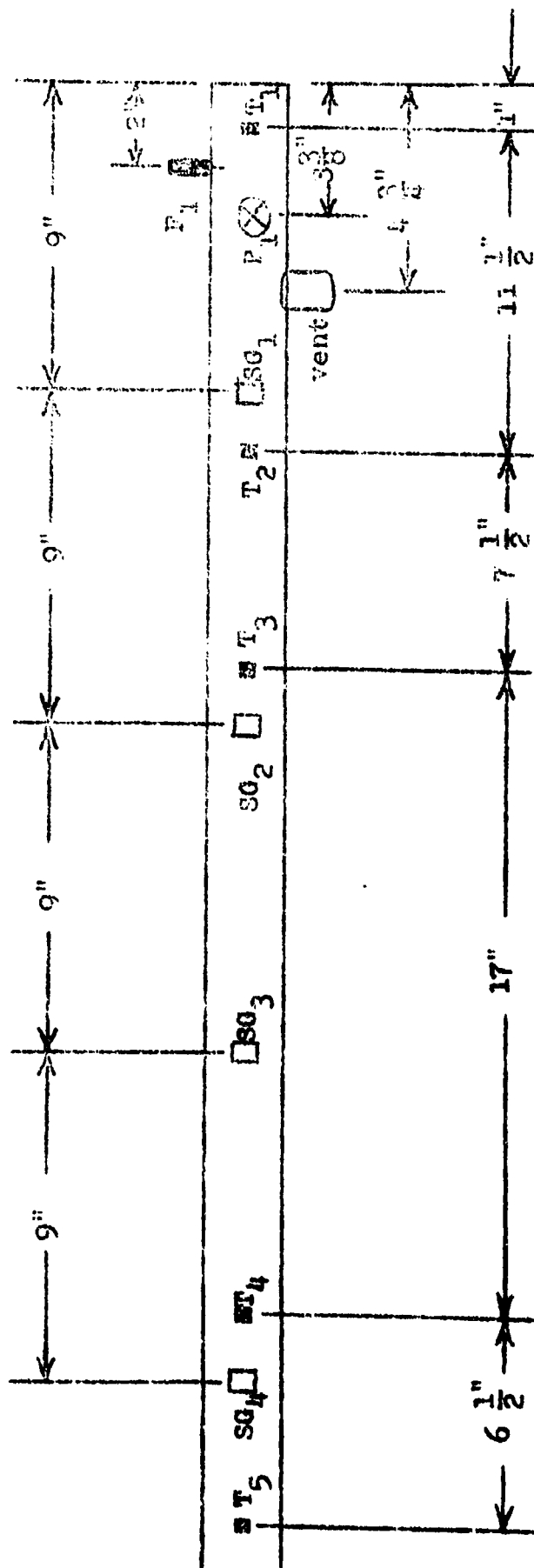


TEST PIPE WITH SPARKING DEVICE
FIGURE 6

- 1) SPARKING DEVICE
- 2) FLAME PROBE
- 3) TEMPERATURE PROBE
- 4) STRAIN GAUGE
- 5) VENT LINE

FIGURE 7

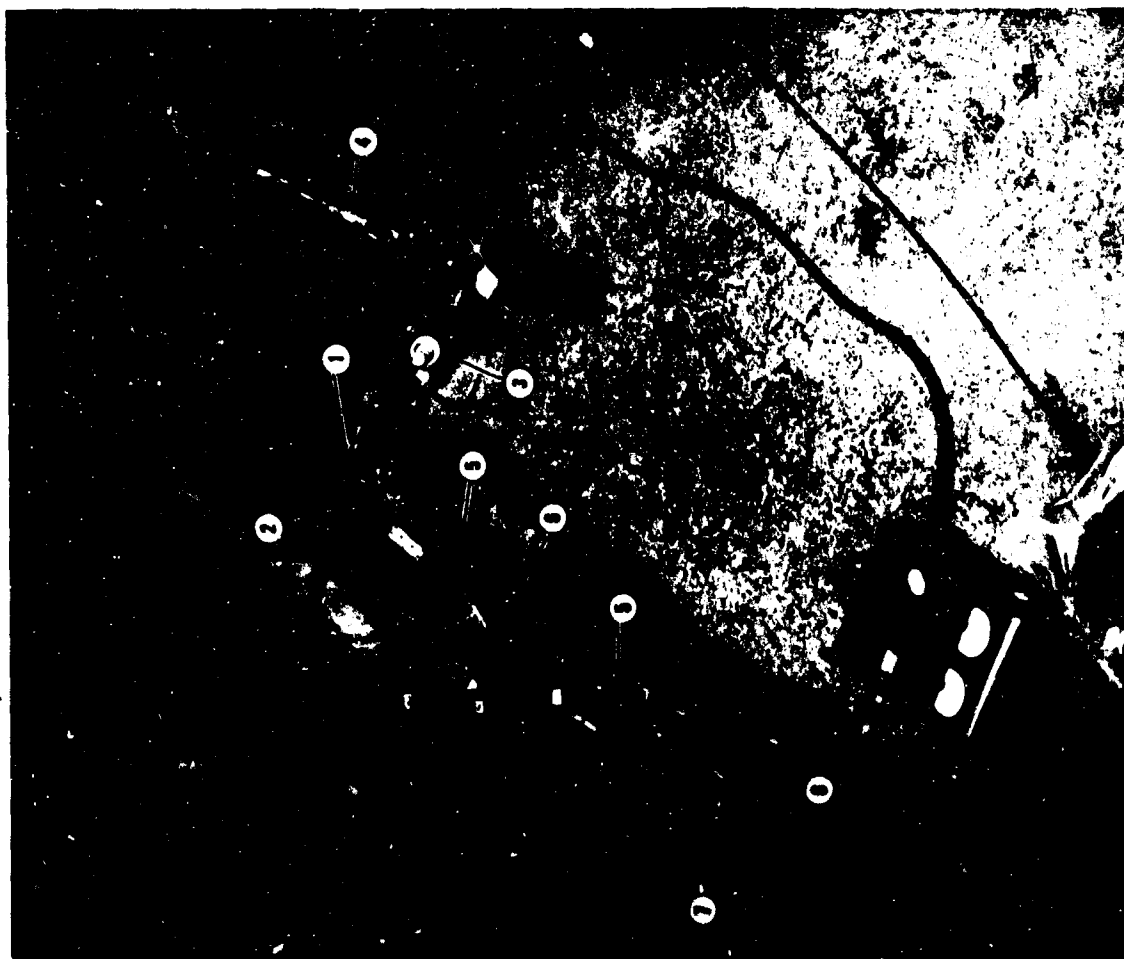
- T - Thermocouple
- F - Flame Probe
- P - Pressure Transducer
- SG - Strain Gauge



Pipe Length: 45 1/2"

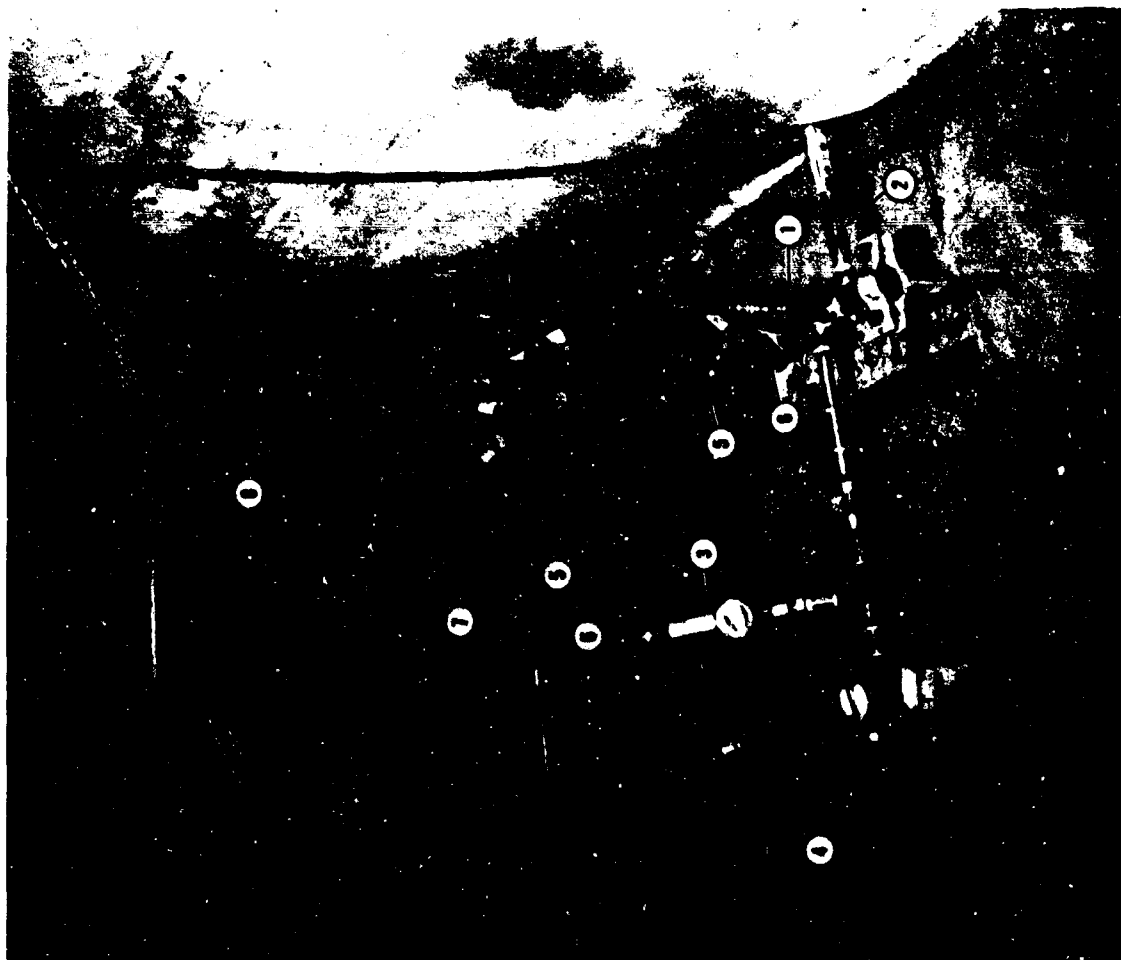
MODIFIED TEST PIPE
FIGURE 8

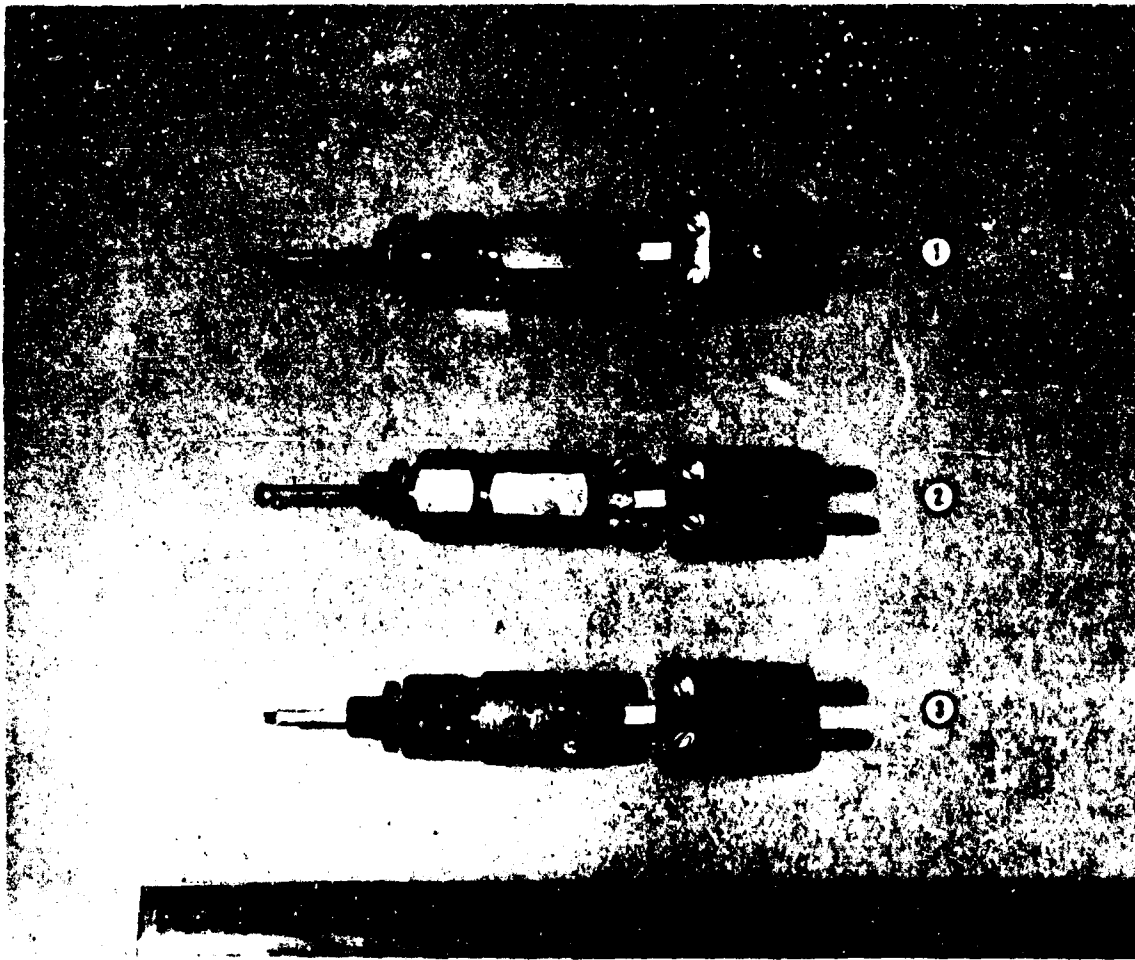
- 1) PRESSURE TRANSDUCER
- 2) FLAME PROBE
- 3) RELIEF VALVE
- 4) GAS SAMPLING BOMB
- 5) STRAIN GAUGES
- 6) HEATING WIRE
- 7) MONEL UNION



MODIFIED TEST PIPE
FIGURE 9

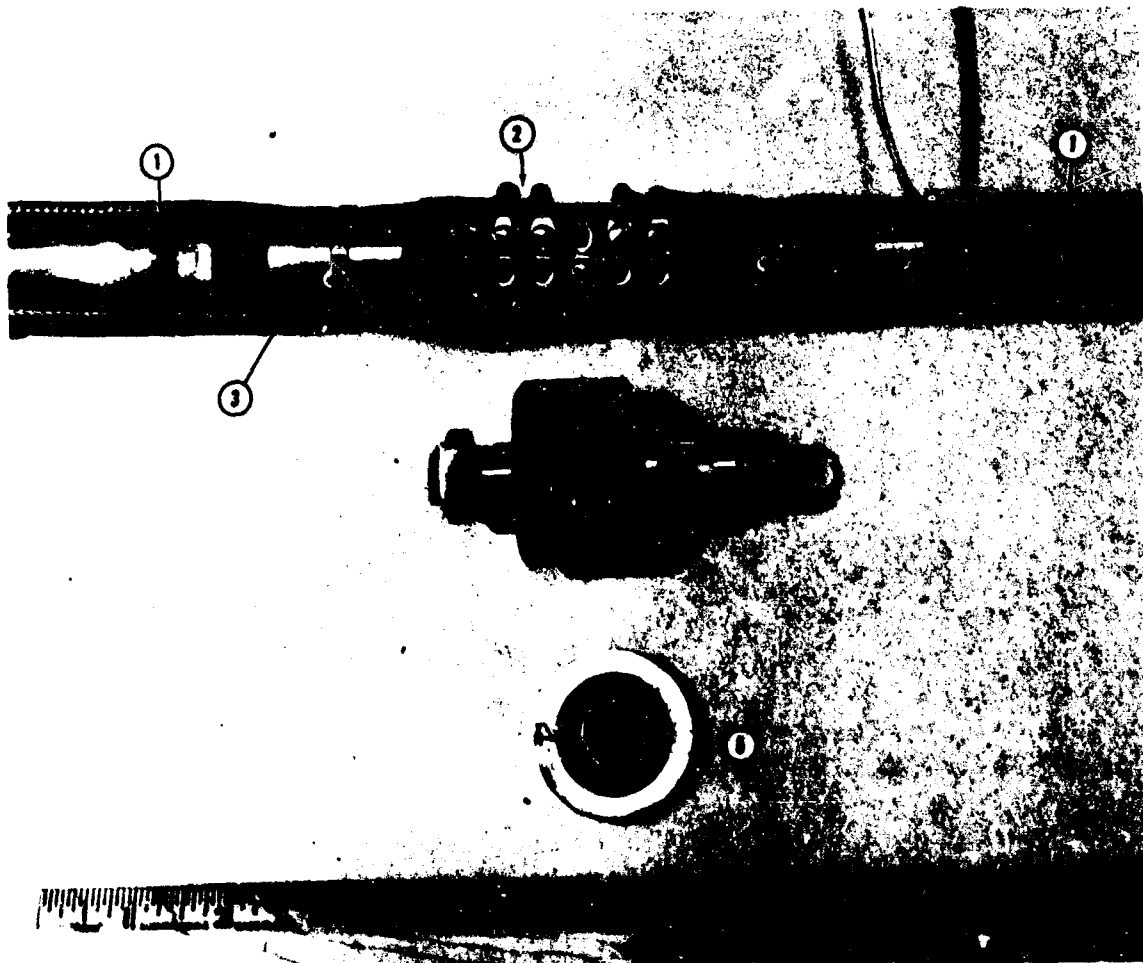
- 1) PRESSURE TRANSDUCER
- 2) FLAME PROBE
- 3) RELIEF VALVE
- 4) GAS SAMPLING BOMB
- 5) STRAIN GAUGES
- 6) HEATING WIRE
- 7) MONEL UNION
- 8) MAROTTA VALVE





INSTRUMENTATION PROBES
FIGURE 10

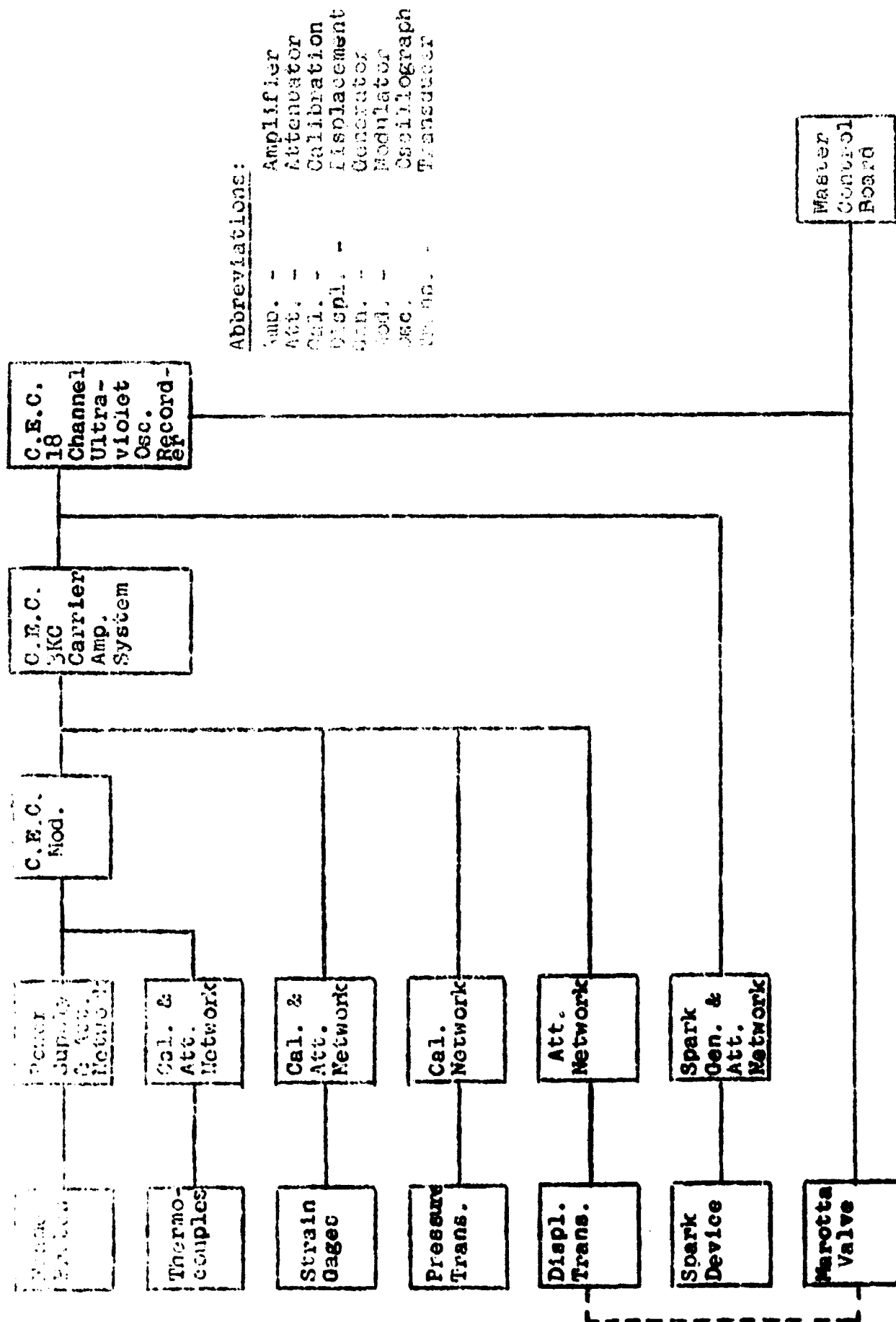
- 1) SPARKING DEVICE
- 2) THERMOCOUPLE
- 3) FLAME PROBE



TEST PIPE COMPONENTS
FIGURE 11

- 1) STRAIN GAUGE
- 2) TERMINAL FOR STRAIN GAUGES
- 3) HEATING COIL
- 4) PRESSURE TRANSDUCER
- 5) FLAME ARRESTOR

OIL CONTAMINATION IN OXYGEN SYSTEMS
INSTRUMENTATION BLOCK DIAGRAM - FIGURE 12



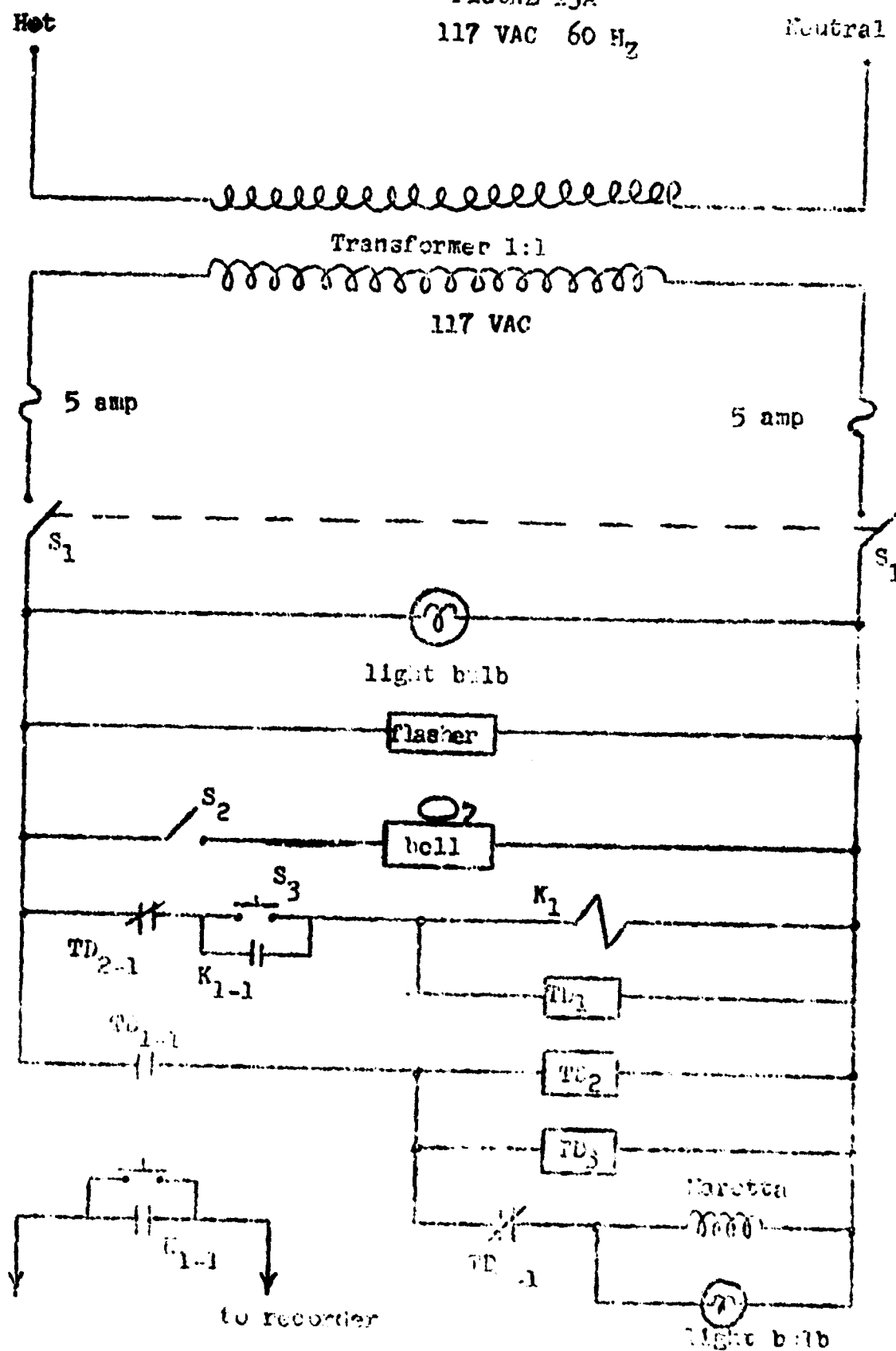
OIL CONTAMINATION IN OXYGEN SYSTEMS
AUTOMATIC REMOTE CONTROL CIRCUIT

FIGURE 13A

117 VAC 60 Hz

Neutral

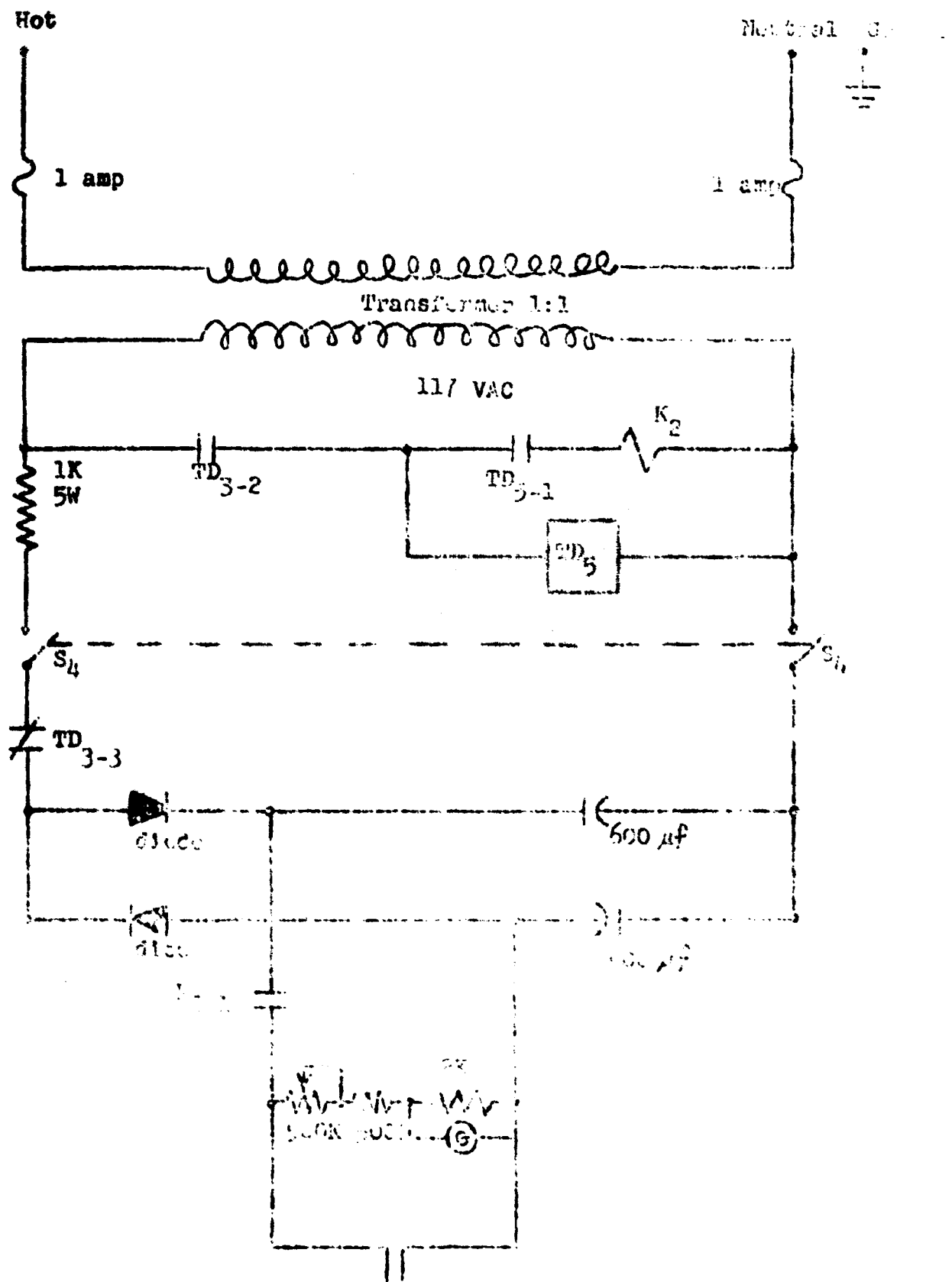
Ground

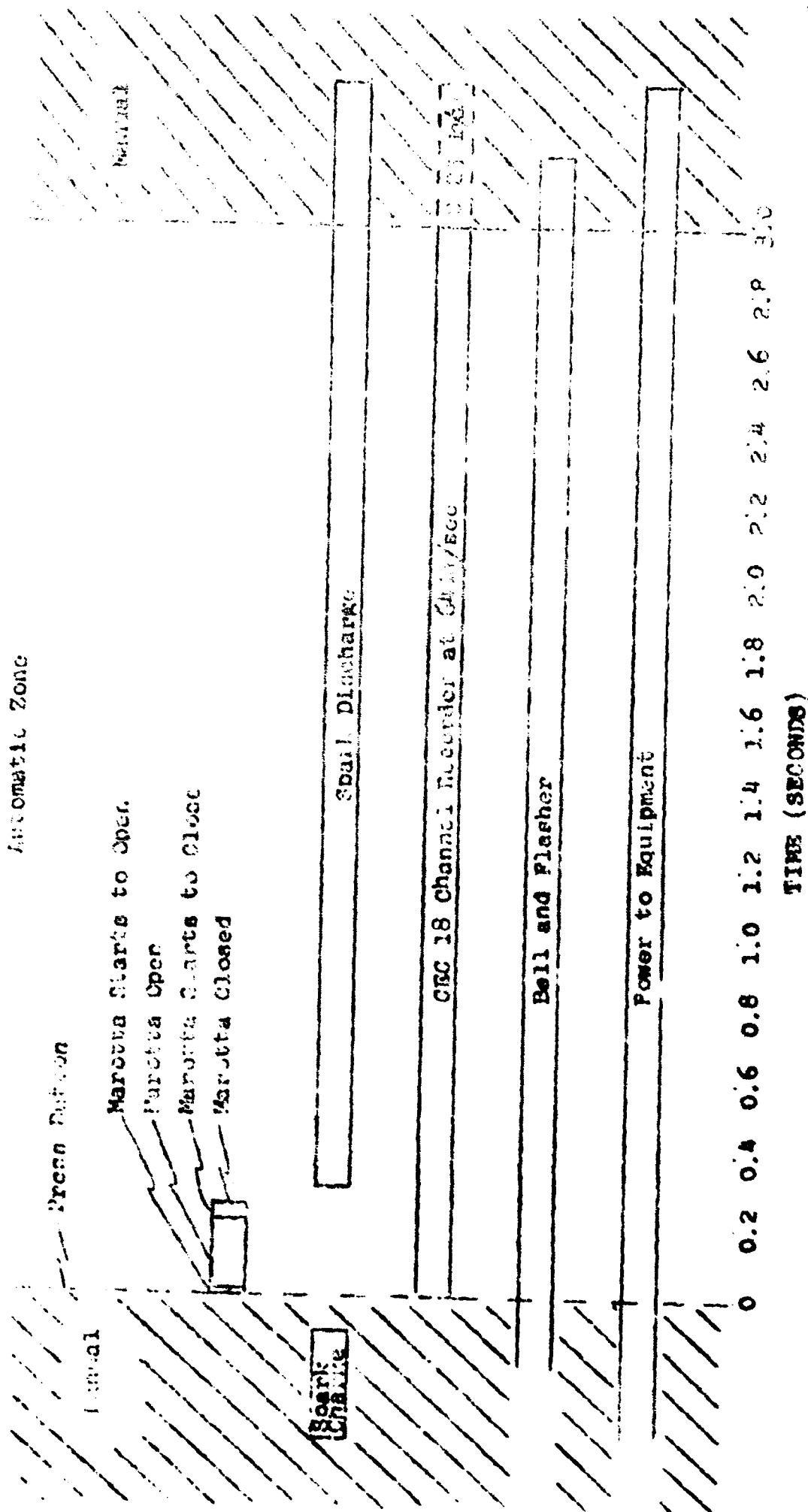


SPARK GENERATOR CIRCUIT

FIGURE 13B

117 VAC 60 H_Z

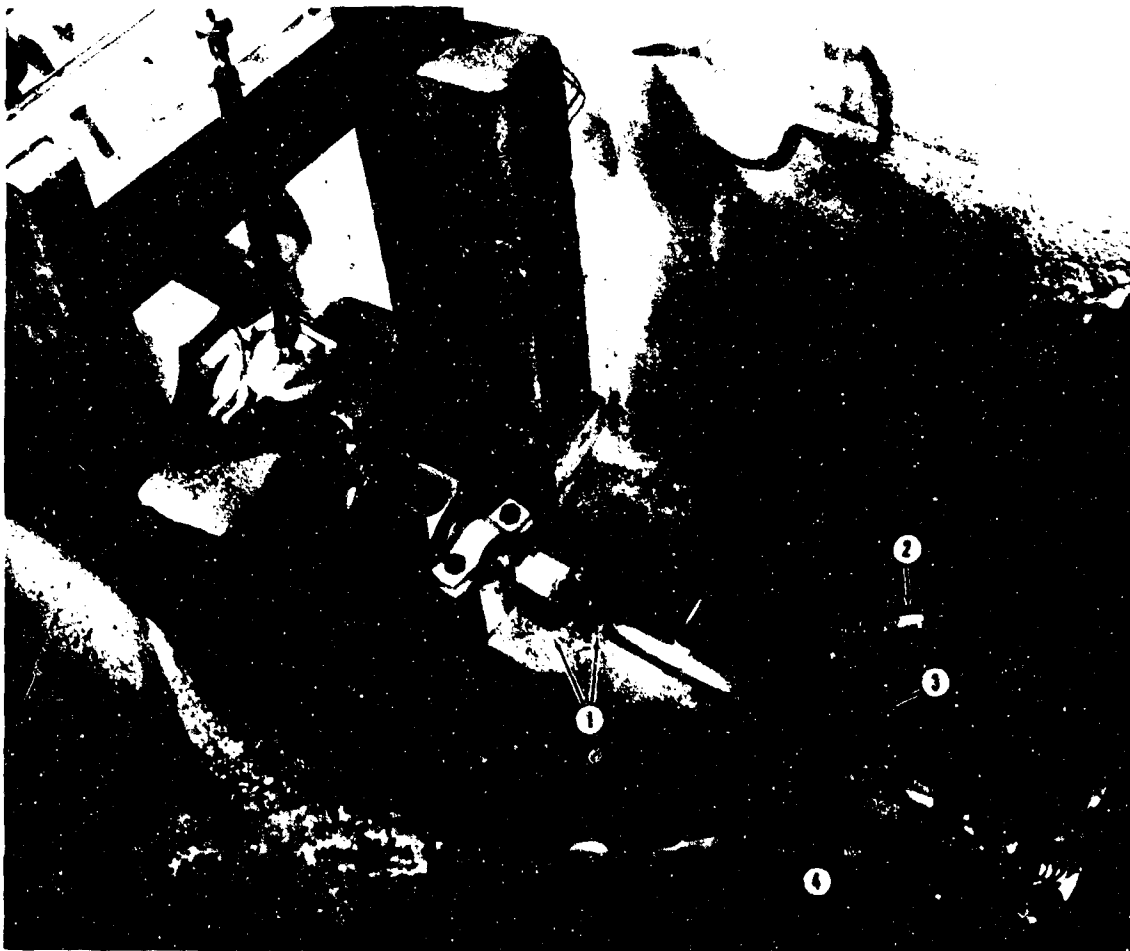






TEST PIPE AFTER EXPLOSION
FIGURE 15

- 1) BURNED UNION AND TEST PIPE FITTING
- 2) CHARRED, BENT FLAME PROBE
- 3) BENT THERMOCOUPLE CONNECTOR
- 4) MELTED, EMPTY PRESSURE TRANSDUCER BOSS
- 5) DISPLACED STRAIN GAUGE TERMINALS
- 6) DISPLACED COPPER O-RING ON PRESSURE TRANSDUCER
- 7) RELIEF VALVE



TEST PIPE AFTER EXPLOSION
FIGURE 16

- 1) MELTED UNION AND TEST PIPE FITTING
- 2) BROKEN THERMOCOUPLE
- 3) MELTED, EMPTY PRESSURE BOSS
- 4) DISPLACED STRAIN GAUGE TERMINAL



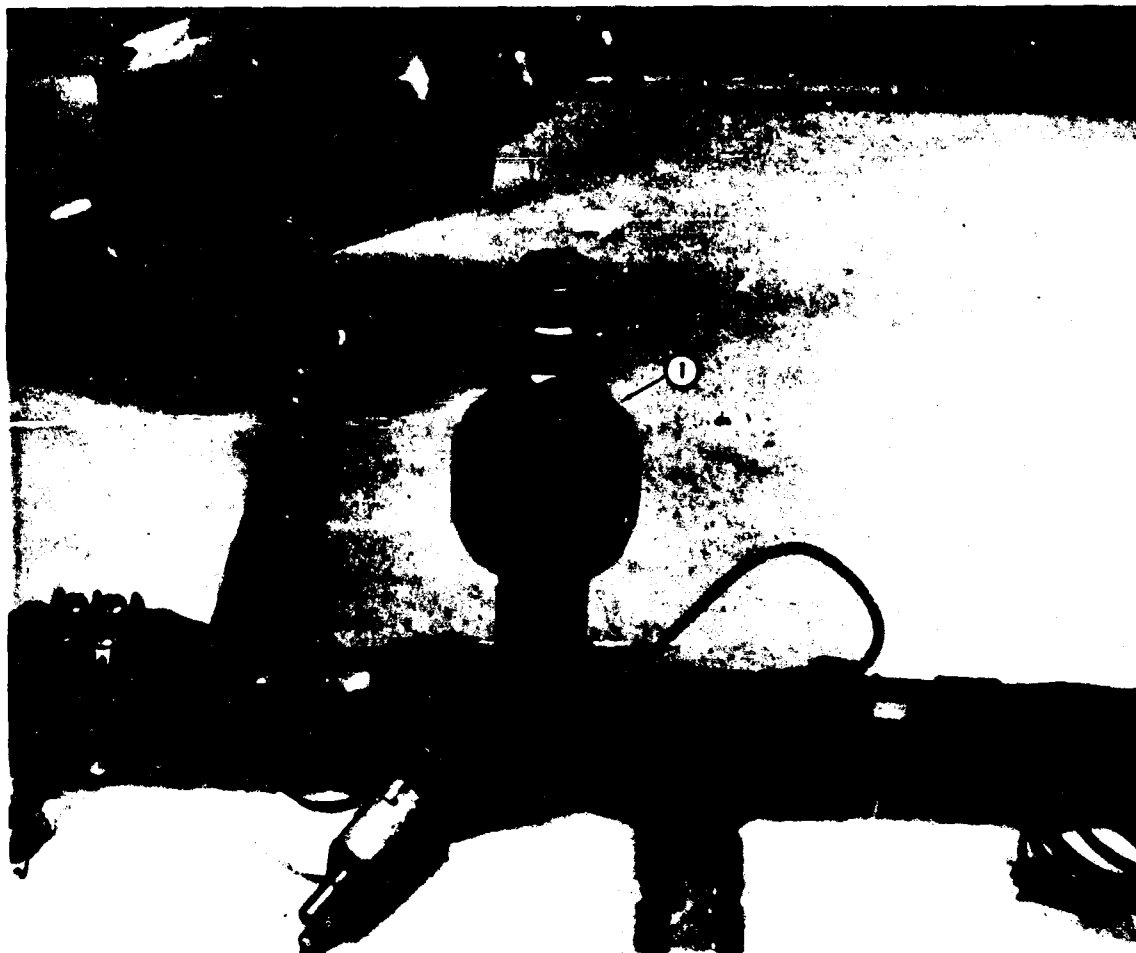
TEST PIPE AFTER EXPLOSION
FIGURE 17

- 1) MELTED UNION
- 2) MELTED TEST PIPE FITTING FRAGMENTS
- 3) TEST PIPE



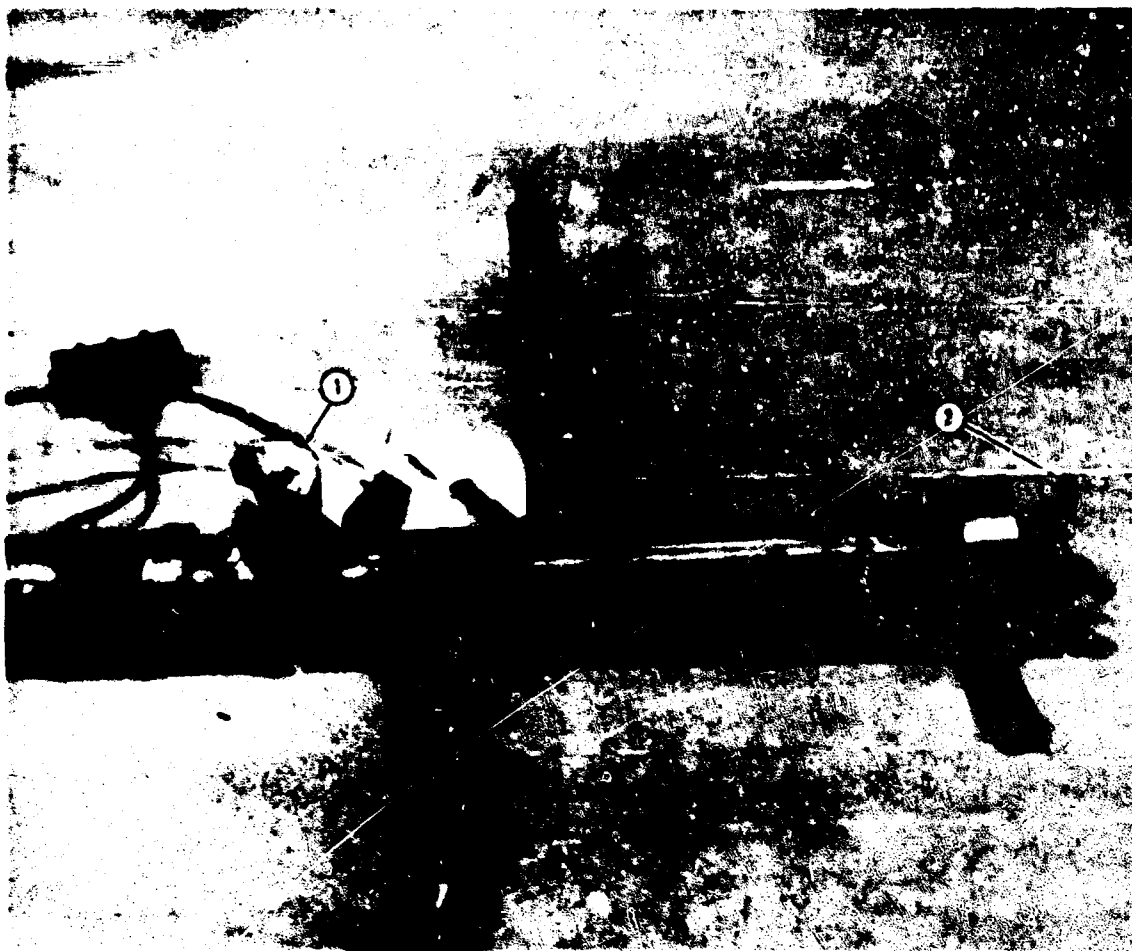
PRESSURE TRANSDUCER AFTER EXPLOSION
FIGURE 18

1) PRESSURE TRANSDUCER FITTING



PRESSURE TRANSDUCER AFTER EXPLOSION
FIGURE 19

1) DISPLACED, BENT COPPER O-RING ON PRESSURE TRANSDUCER



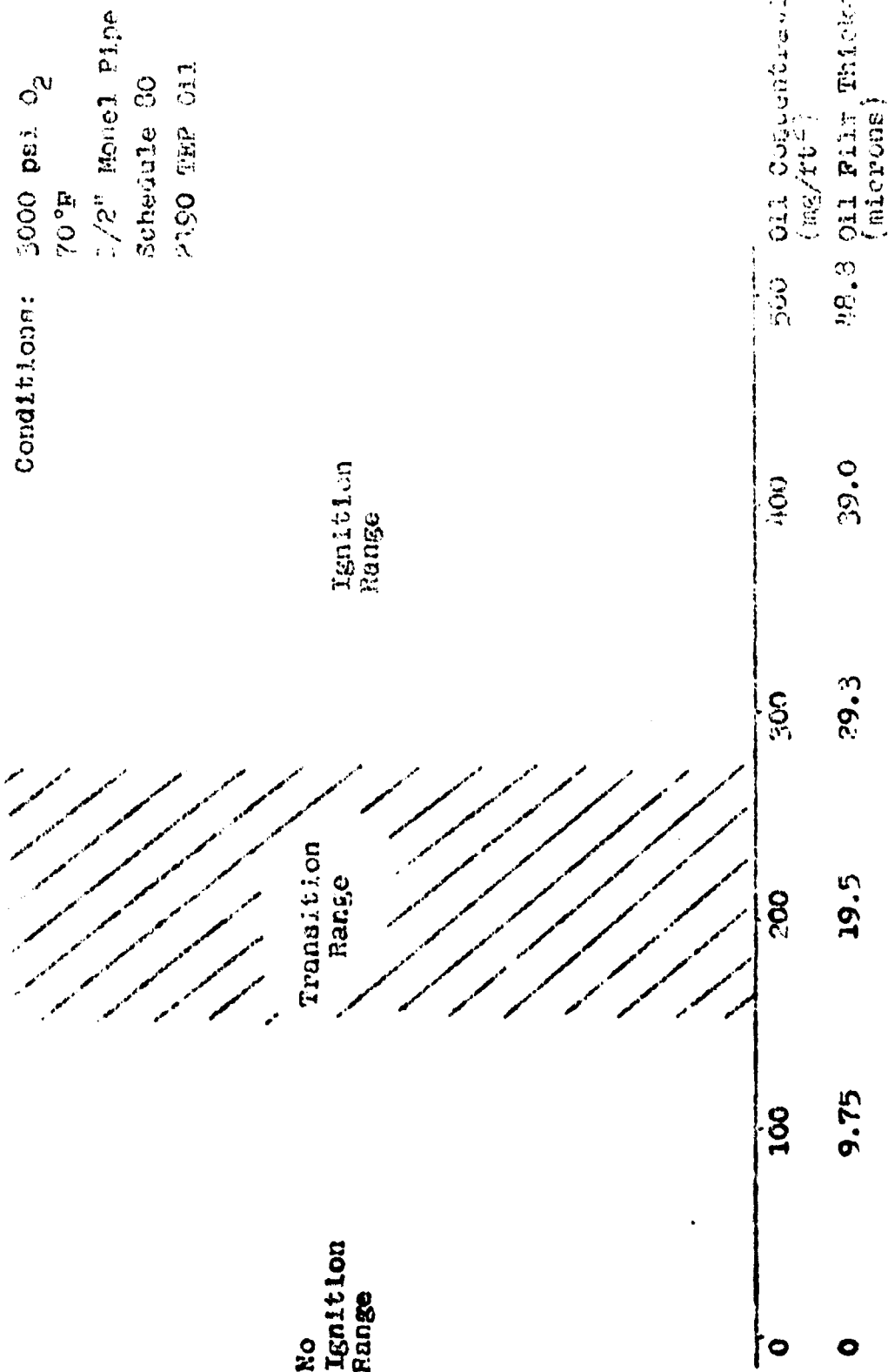
INSTRUMENTATION BOSS AFTER EXPLOSION
FIGURE 20

- 1) MELTED PRESSURE TRANSDUCER BOSS
- 2) MELTED TEST PIPE FITTING

OIL CONTAMINATION IN OXYGEN SYSTEMS

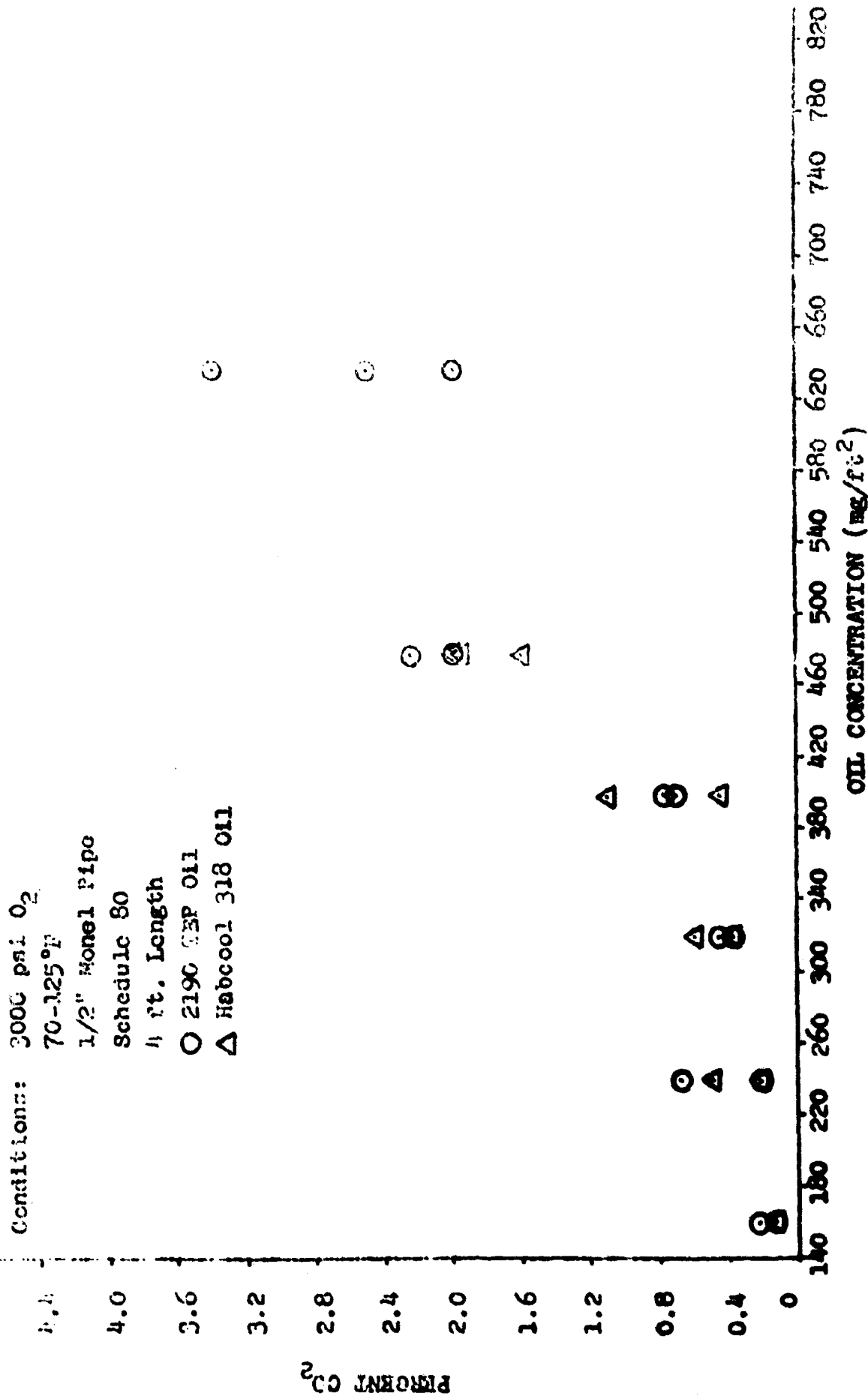
IGNITION/NO IGNITION RANGES

FIGURE 21



PERCENT CO_2 VS. OIL CONTAMINATION

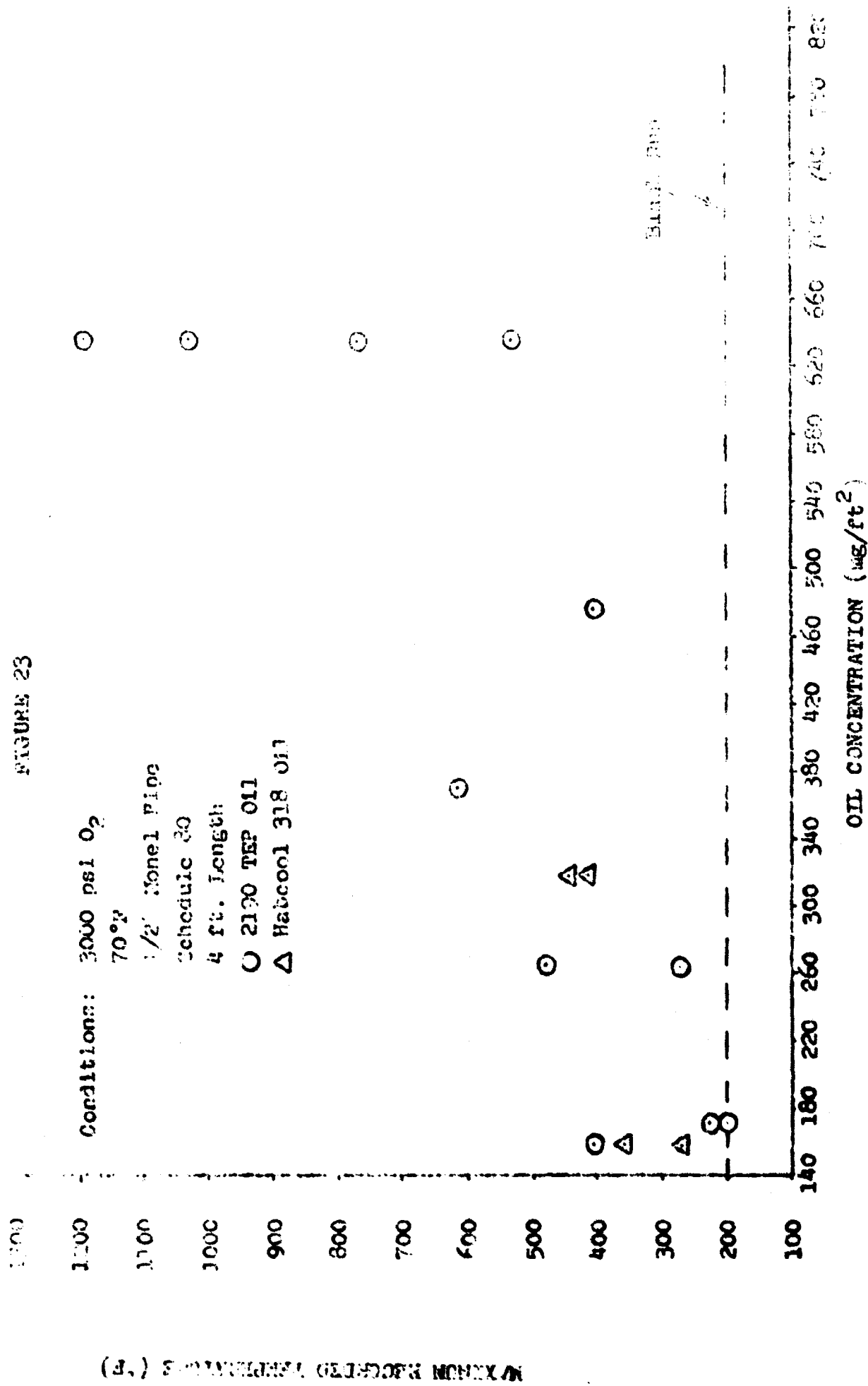
FIGURE 22



OIL CONTAMINATION IN OXYGEN SYSTEMS

MAXIMUM PERMITTED TEMPERATURE VS. OIL CONCENTRATION

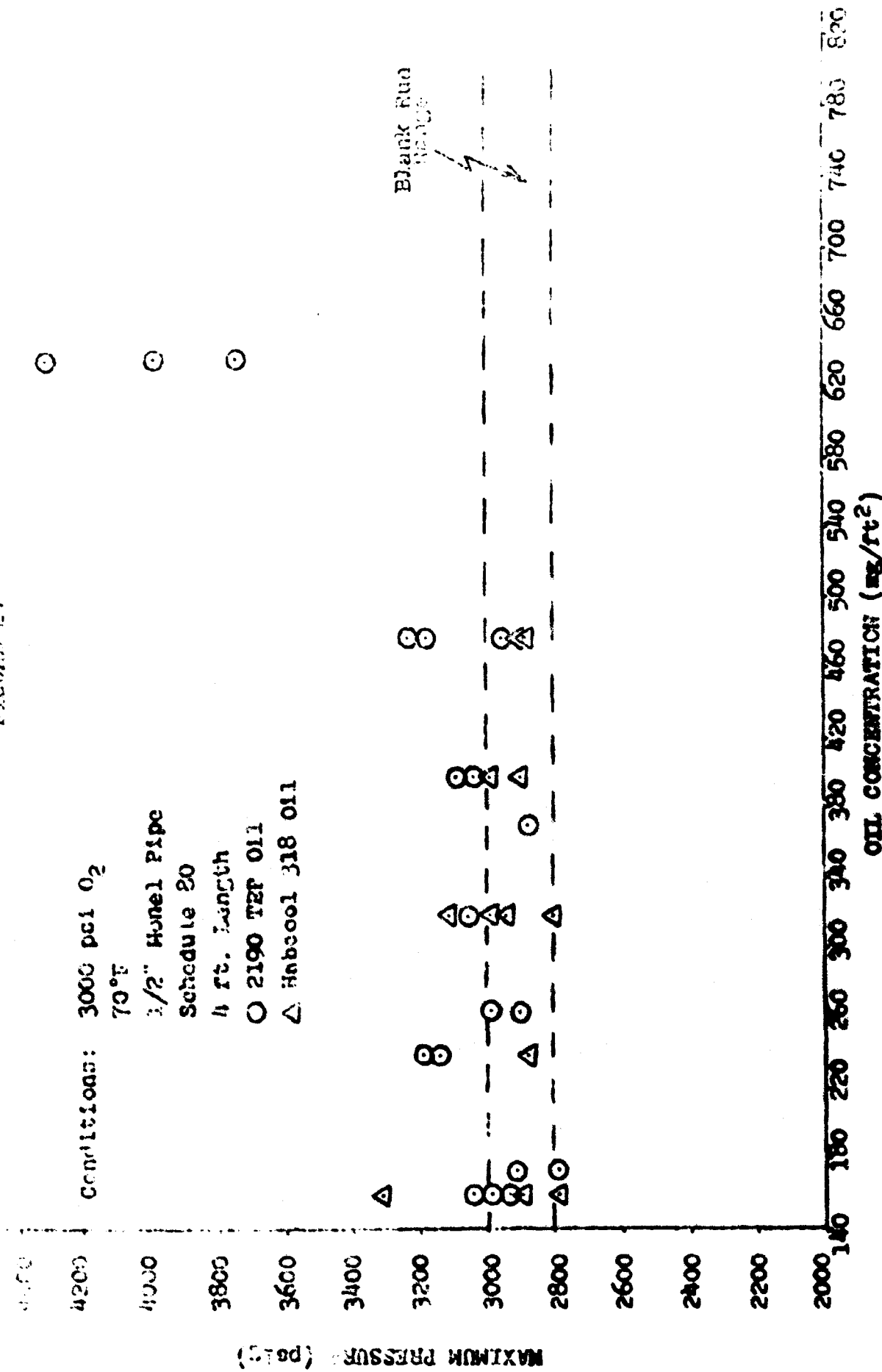
FIGURE 23



Oil Oxidation in Oxygen Systems

Oil, 100% Sulfonated 100% Oil Concentration

FIGURE 24



UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified.)

| | | | |
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| 4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final Report (July 1967 - Aug 1967) | | | |
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| 13. ABSTRACT <p>The ignition limits of 170 lubricating oil and Lubrol #31 cutting oil evenly coated on a 1/2" nominal pipe exposed to 3000 psi O₂ were determined. Little danger of ignition or flame propagation exists below oil concentrations of 160 mg/ft³; while concentrations above 160 mg/ft³ will ignite in a pure O₂ atmosphere.</p> | | | |

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| <p>Compression Ignition Oxygen Systems Cleaning Procedures</p> | | | | | | | |
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